High Frequency Way of Helium Ash Removal from Stellarator-Reactor

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Abstract. The paper deals with the problem of helium ash removal from stellarator-reactor. The lower hybrid heating of ash ions is proposed to solve this problem. The theory of ion stochastic heating, developed earlier by Karney, is generalized on the case of heating in stellarators. The features of the lower hybrid waves propagation and the ions motion in the stellarator confining field are taken into account. With proper choice of wave parameters (such as frequency, antenna position and initial spectrum of longitudinal refractive index) the slow mode of LH waves penetrates from the launching system to plasma core (and back) without conversion to kinetic plasma mode or to fast mode. With all these going on, the LH wave is absorbed by alpha particles only. The electron Landau damping is negligibly small, and there is no bulk ions stochastic heating. The motion of high energy (>100 keV) ions in the LHD heliotron with inwardly shifted magnetic axis, as an example of stellarator type device, is calculated numerically using the single particle simulation code which couples modified Karney's ion stochastic heating theory. The effect of collisions was taken into account through the Monte Carlo equivalent of the Lorentz collision operator. It is shown, that due to interaction with lower hybrid wave, initially well-confined alpha particles are expelled from the plasma during the time period less then collision time. At the same time, the low hybrid heating does not remove the ions with energy higher than 500 keV. Therefore, it is possible to use this method of RF heating for helium ash removal in stellarator-reactor. The required LH power is estimated to be of the order of 10 MW.

1. Introduction

As a result of the development of the concept of a drift-optimized stellarator configuration, the main requirement for a construction of current devices is single particle confinement in the plasma core region during a long period of time. The confinement of high-energy ions in the core region depends weakly on the particle pitch value λ at the particle start point (here $\lambda = V_{\|}/V$ with $V_{\|}$ being the parallel velocity of the particle motion along the magnetic field lines, and V being the full particle velocity). As the subsidiary issue, the cooled alpha particles could be accumulated in the plasma core and lower the efficiency of the reactor operation. Now this problem is under discussion for tokamaks [1-4], but it is also an important question for stellarators [5,6]. It was concluded in Ref. 5 that due to resonances between trapped alpha particles and drift waves significant loss of particles with energy 352 *keV* is stimulated without destroying the confinement of hot alpha particles. Using of the variation of the helical field amplitude in time for ash removal in the helical device was proposed in Ref. 6. The authors of both papers underlined that confinement of the bulk plasma should not deteriorate.

It is well known from the tokamak experiments that at the lower hybrid (LH) heating of tokamak plasmas, the regime of ion stochastic heating [7] can be realized. In this case the ions with $V_{\perp} \geq \omega/k_{\perp}$ ($V_{\perp}$ is the velocity component of the particle motion perpendicular to the magnetic field lines, $k_{\perp}$ is the LH wave vector in the same direction, and ω is the wave frequency) acquire the perpendicular kinetic energy. In spite of the fact, that interaction of lower hybrid waves with fusion alpha particles in tokamaks have been considered by many authors (i.e., [8-12]), they mainly paid attention to the influence of alpha particle – LH wave interaction on the efficiency of current generation. Still it is worth noting that this interaction

possesses the intrinsic energy selectivity. In particular, this feature is necessary for helium ash removal.
So, it is interesting to clarify the following question: whether the LH heating could affect the high-energy ion confinement in a stellarator.

2. Model and Calculation Details

While solving this problem, we should take into account some important features. The ions motion is the result of two actions. The first one is the ion guiding centre motion in the confining magnetic field. It is modified by the LH heating due to the change of both the ion kinetic energy and pitch. The second one is the ion cyclotron rotation and the ion interaction with LH wave during this rotation. It is also modified at the guiding centre motion because of a space change in both the LH wave amplitude and conditions of the wave-particle interaction.

2.1. Magnetic Configuration and Basic Equations

The LHD heliotron with the magnetic axis shifted inwardly with respect to the geometrical centre is an example of optimized configuration with an improved particle confinement. The representation of the magnetic field along a field line was taken as

$$B/B_0 = \sum_{j=1}^{6}\sum_{N=-3}^{3} \varepsilon_{j,N}(r)\cos[j\theta_0 + \varepsilon_t(\iota j - NM)\chi], \tag{1}$$

where r, θ_0, χ are Boozer's magnetic coordinates, j is the poloidal mode number, N is the toroidal mode number, M is the number of magnetic field periods along the device length, B_0 is the averaged value of the magnetic field at the geometrical axis of the device. In drift approximation, motion of guiding centre is described by equations

$$\frac{dr}{dt} = -\frac{V_D}{r}\frac{\partial b}{\partial \theta_0}, \quad \frac{d\theta_0}{dt} = \frac{V_D}{r}\frac{\partial b}{\partial r}, \quad \frac{d\chi}{dt} = \Omega_\chi, \quad \frac{dV_\parallel}{dt} = -\omega_c V_D \frac{\partial b}{\partial \chi}, \tag{2}$$

Here $b = B/B_0$, $V_D = V_{\nabla B} + V_{cur}$ is the particle drift velocity due to the gradient–B drift ($V_{\nabla B}$) and the curvature drift (V_{cur}), where $V_{\nabla B} = \mu c/e$, and $V_{cur} = mcV_\parallel^2/eB$, μ is the particle magnetic moment, $\Omega_\chi = V_\parallel/R$ is the toroidal transit frequency. The last closed flux surface was adopted as a loss boundary. The integration step equals to 1/6 of alpha cyclotron period. While carrying out the influence of collisions on alpha particle – LH wave interaction both the deflection of alpha particles on ions and alpha particles energy scattering considered, using the Monte Carlo equivalents of Lorentz collision operators [13] after each time step. The dependence of deflection collision frequency ν_d and energy collision frequency ν_E on plasma density and alpha particles energy was taken into account.

2.2. LH Heating in Stellarators

The proper choice of wave parameters (such as $\omega/\omega_{pi}(0)$, antenna position and initial spectrum $N_\parallel$) may provide LH wave propagation (slow mode) from launching system to plasma core (and back) without conversion to kinetic plasma mode or to fast mode. As $Z_e >> 1$, the electron Landau damping is negligibly small. For bulk ions $V_\perp < \omega/k_\perp$ is fulfilled ($k_\perp$ is transverse to confining field component of a wave vector). So, there is no bulk ions stochastic heating. With this going on, the LH wave is absorbed by alpha particles only. Because of assuming the density of alpha particles to be low, the LH wave absorption is small. As a consequence, the LH waves propagate from antenna to plasma core and back to plasma edge, and spread over the whole plasma volume. So we put $N_\perp \approx \sqrt{|\varepsilon_3/\varepsilon_1|}N_\parallel$. As $E_\perp \approx N_\perp E_\parallel / N_\parallel >> E_\parallel$, then we have for LH wave amplitude $E_0 \approx E_\perp$. Based on [14], the dependence $N_\parallel = N_{\parallel 0}(1 + C_1 b)$ was assumed.

2.3. LH Wave – Alpha Particle Interaction

Let us consider the cyclotron motion of the high-energy ion with the perpendicular velocity $V_\perp$ and its interaction with LH wave of amplitude E_0. Our simulation of the ion stochastic heating in a stellarator is based on the classical Karney's paper [7]. The ion stochastic heating takes place when the following conditions are satisfied

$$\alpha = N_\perp \nu \frac{E_0}{B} > \frac{\nu^{2/3}}{4} = \alpha_{min}, \tag{3}$$

$$r_{min} = \nu - \sqrt{\alpha} < r_{LH} < r_{max} = (2/\pi)^{1/3}(4\alpha\nu)^{2/3}. \tag{4}$$

Here $N_\perp = k_\perp c/\omega$. is the perpendicular component of the LH wave refractive index, $\nu = \omega/\omega_{c\alpha}$, $\omega_{c\alpha}$ is the cyclotron frequency of alpha particles, $r_{LH} = k_\perp V_\perp / \omega_{c\alpha}$. Owing to the dependence of the wave parameters on both space coordinates and change in $V_\perp$ during the motion of ion guiding center, the interaction conditions (3) and (4) will vary from point to point. If the conditions do fulfill at *i*-s step of integration, then ions $V_\perp$ and, as consequence, magnetic moment μ, kinetic energy W and pitch parameter $\lambda = V_\parallel / V$ change. Current time along the ions trace changes too:

$$r_{LH}^{i+1} = r_{LH}^{i} + \frac{\nu}{r_{LH}} A \cos\varphi^i \cos\rho^i,$$

$$t^{i+1} = t^i - \frac{\sqrt{r_{LH}^2 - \nu^2}}{r_{LH}^2} A \sin[\varphi^i + \nu\pi - \pi A\cos(\rho^i + \varphi^i)] \sin[\rho^i - \nu\pi + \pi A \cos(\rho^i + \varphi^i)].$$

Here $\rho = (r_{LH}^2 - \nu^2)^{1/2} - \nu \arccos\frac{\nu}{r_{LH}} - \frac{\pi}{4}$, A is directly related to α,

$$\varphi^i = (\omega - k_\parallel V_\parallel)t^i + \varphi_0 \tag{5}$$

is phase of wave-ion interaction with φ_0 being the initial random phase. As distinct from Karney's approach, we take into account that both $N_\parallel$. and r_{LH} vary along the ion trace. The r_{LH} value changes due to variation of $k_\perp$ at LH ray and change of ion $V_\perp$ while ion moves in inhomogeneous magnetic field $B = B(\vec{r})$. Besides, ion cyclotron rotation period changes due to magnetic field inhomogeneity, causing deviation in φ. In addition, the dependence of E_0 on $\vec{r}$ gives rise to spatial variation of ion stochastic heating margins.

3. Simulations of LH Wave – Alpha Particle Interaction

To have the problem solved, we studied the high-energy ions behaviour in a real stellarator geometry using the single particle simulation code which couples ion stochastic heating theory. For plasma and LH wave parameters we put $n_i(0)=10^{20}\,m^{-3}$, $n_i(r)=n_i(0)\left(1-0{,}9r^2/a^2\right)$, $\omega/\omega_{pi}(0)=1{,}5$, $\nu(0)\approx 50$, $T_e=5\,keV$, $N_{\parallel 0}=1{,}4$, C_1=0,7, $E_0=12\,kV/cm$ at $r=0$.

3.1. Details of LH Wave – Alpha Particle Interaction

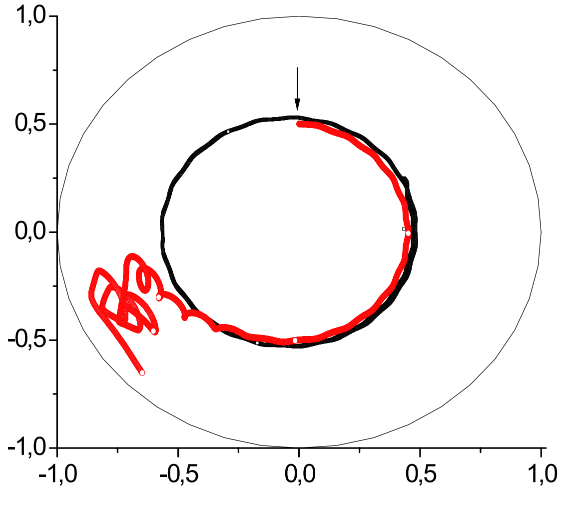

Fig.1. Projection on the minor cross-section of the trace of passing α particle W_0 = 100 keV, λ_0 = -0,6, r_0/a = 0,5, θ_0 = π/2. LH is turned off (black), LH is turned on (red).

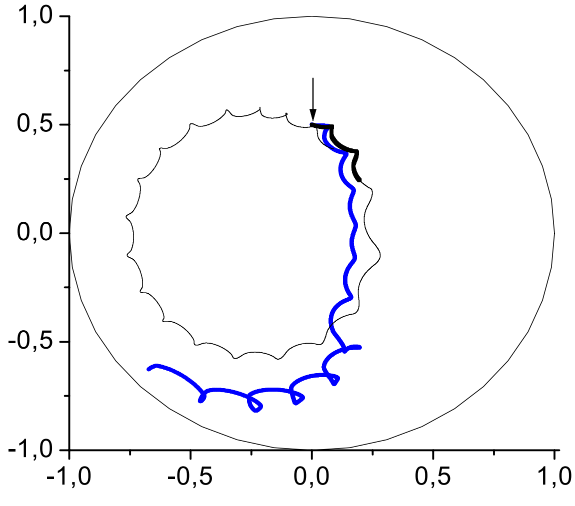

Fig.2. Projection on the minor cross-section of the trace of trapped α particle W_0 = 100 keV, λ_0 = -0,2, r_0/a = 0,5, θ_0 = π/2. LH is turned off (black), LH is turned on (blue).

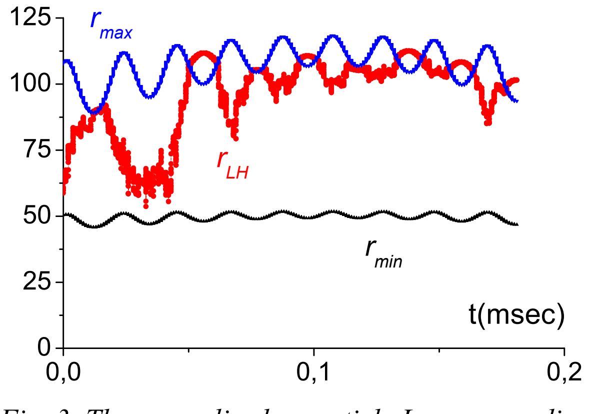

Fig. 3. The normalized α particle Larmour radius r_{LH} and margins of stochastic LH wave – particle r_{min}, r_{max} interaction along the trace vs time.

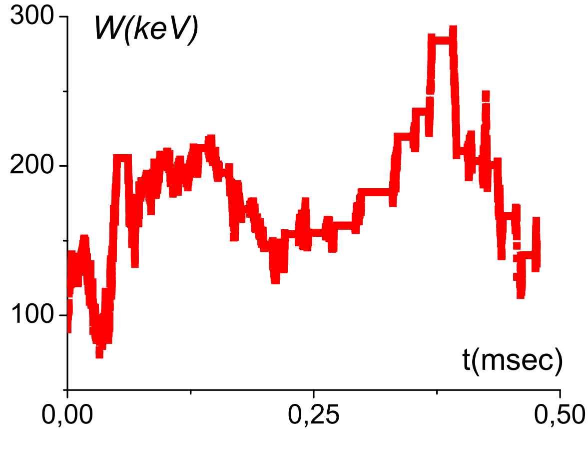

Fig.4. The kinetic energy of α particle W_0 = 100 keV, λ_0 = -0,6 along the trace vs time.

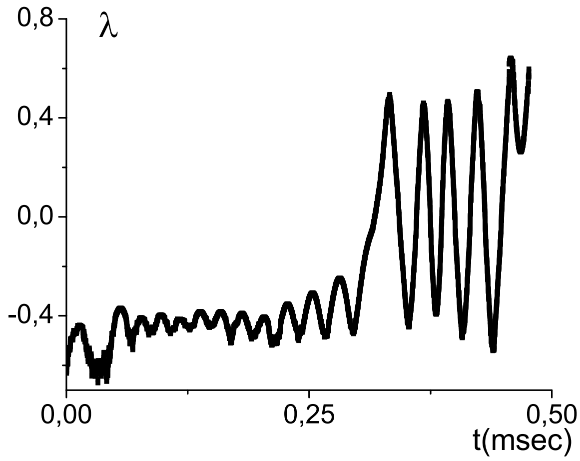

Fig.5.The pitch parameter of α particle (W_0 = 100 keV, λ_0 = -0,6) along the trace vs time. LH is turned on.

Here and further the radial position of particle initial point was *r/a=0,5*. As it is shown in Fig. 1, Fig.2, well-confined passing alpha particle is expelled from plasma volume after interaction with LH wave. The process of LH wave – alpha particle interaction is rather complicated. The interaction intervals alternate with periods when the necessary conditions (3), (4) are not fulfilled (Fig. 3). While the ion is moving in the stellarator confining field, the kinetic energy retrieving intermits by energy loss or energy conserving (Fig.4). Since $V_\perp$ is the only component of the particle velocity, that changes its value during heating, the main effect of heating on guiding centre motion is consisted in the change of the particle pitch (see Fig.5). The radial component is the main part of both $N_\perp$ and $E_\perp$. Therefore, a shift of the particle guiding centre (directed in $\vec{E}_\perp \times \vec{B}$) occurs mostly in the poloidal direction. Its value is negligibly small.

3.2. The Probabilistic Approach

The particle removal from the confinement volume is the principal outcome of LH wave – alpha particle interaction. Whether this event happens or not, depends on the random initial phase of interaction. As the initial phase of interaction is random, the result is random too.

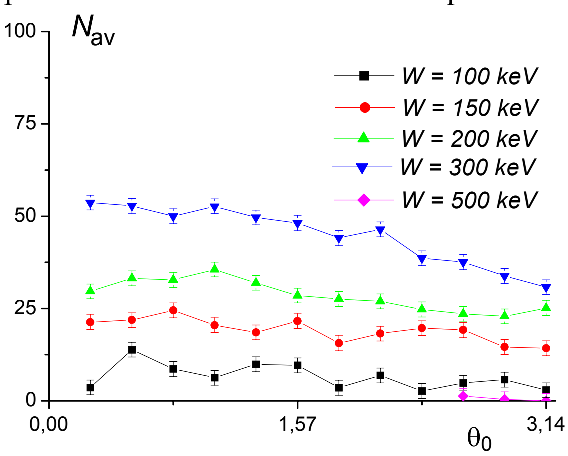

Fig.6. The averaged fraction of removed α (%) vs initial poloidal angle for different initial α energy (λ=-0,5). Only the calculations for well- confined particles are shown.

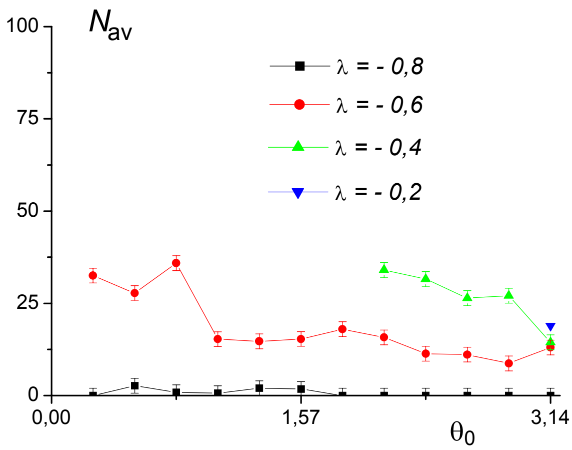

Fig.7. The averaged fraction of removed α (%) vs initial poloidal angle for different initial α pitch (W=150 keV). Only the calculations for well-confined particles are shown.

In order to investigate the process, we took the sampling of 50 particles with all the initial parameters fixed but φ_0, and followed them during 1,5 msec. The total number of sampling was defined by the condition, that averaged number of positive outcomes (removals) is known with the probability 98%. We need to take about 65 sampling, typically. Then, we fix the initial toroidal angle and investigate the dependence of interaction on other parameters. In dependence on the energy, pitch and initial position of particles, some of high energy ions are initially either in the prompt loss cone or near it. These particles were excluded from the consideration. As it is shown in Fig. 6, Fig.8, from 25% to 50% of interacting alpha particles are expelled from confinement volume. The particles of higher perpendicular velocity (magenta line of Fig. 6) or lower perpendicular velocity (black line of Fig. 7) are out of the margins of interaction region, defined by Eq.(4), and are not effected by LH wave. So, the method proposed has pronounced selectivity as to the energy of removed alpha particles.

3.3 Influence of collisions

To investigate the effect of collisions we took the ensemble of 1000 test particles of energy *W=150 keV* randomly distributed over poloidal and toroidal initial angles and over pitch values from -0,5 to –1,0 (see Fig. 8 and Fig. 9). The normalized value of $\nu_d \omega_{c\alpha}$ was put to $2{,}4 \cdot 10^{-8}$ that corresponds to $T_e \approx 5\, keV$.

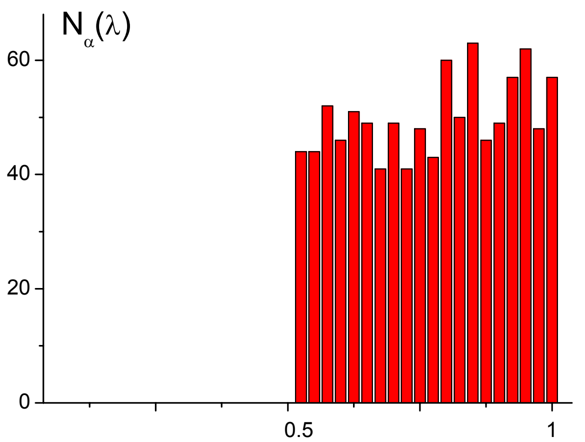

Fig.8. Initial distribution of the test particles over pitch.

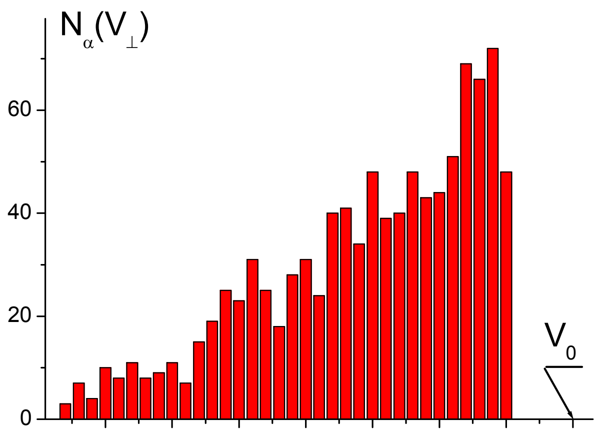

Fig. 9. Initial distribution of the test particles over perpendicular velocity. Velocity v_0 *corresponds to* $v_{\|} = 0$.

Then, these particles were followed during 1,5 msec. When both the LH heating and collisional operators were turned off, all particles were well confined. The cases LH heating is turned on, the collisional operators are turned on and case of combined effect of LH heating and collisions were simulated. The results are shown in Fig. 10 and Fig. 11. As it is seen in Fig. 10, the synergetic effect of LH heating is expressed strongly. The details of the process are shown in Fig. 11. The LH heating increases the perpendicular velocity of alpha particles up to few times of initial velocity v_0, while collisions redistribute particles over pitch. The total effect is rather favourable for particle removing. The influence of the collisional frequency value and wave amplitude value was carried out too (Fig. 12 and Fig.13).

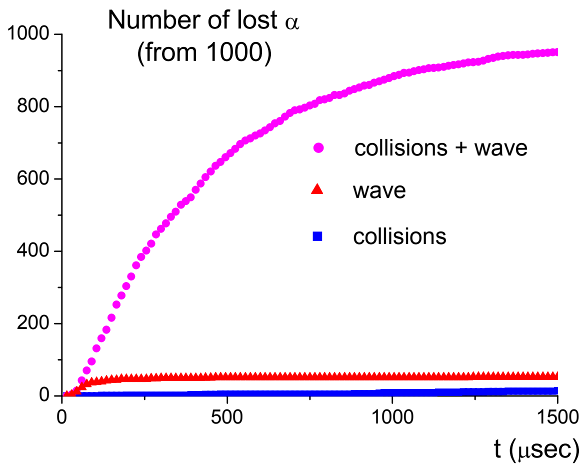

Fig.10. Number of lost particles with initial energy 150 keV vs time.

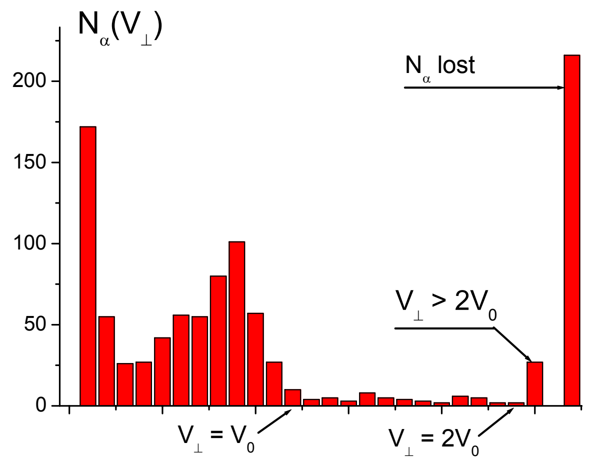

Fig. 11. Distribution over $v_\perp$ of test particles (Fig.9) after 0,15 msec.

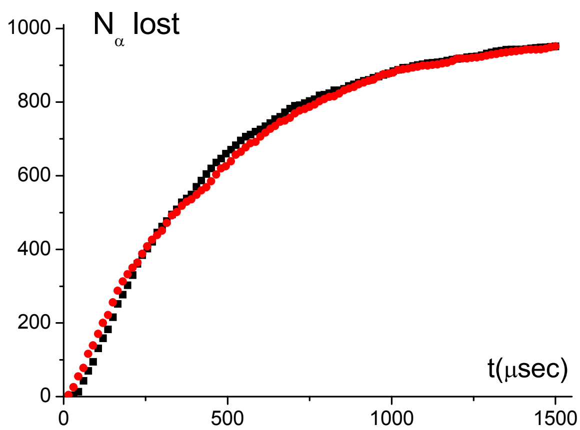

Fig.11. Number of lost particles with initial energy 150 keV vs time. The value of LH wave amplitude $E_0(red)/E_0(black)=3$

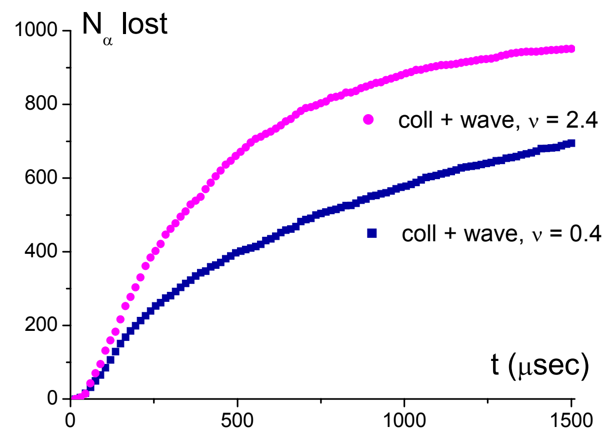

Fig.13. Number of lost particles with initial energy 150 keV vs time. Dark points - $\nu_d \omega_{c\alpha} = 0{,}4 \cdot 10^{-8}$.

Thus, the increase of wave amplitude influences the removal of particles with *W=150 keV* weakly. The decrease of collisional frequency slows down the process of removing, but does not change it essentially. Thus, LH heating provides an effective removal of helium ash ions as far as collisions are taken into account.

4. Conclusion

While simulating the motion of the high-energy ions that initially occupied the region of the “absolute confinement” in a heliotron, we reveal that the LH heating can expel these ions from plasma. Making the proper choice of the wave frequency and initial $N_{\|}$ spectrum, it makes possible to provide the wave damping due to the high-energy ions only. Confirming the statement above, the growth of ions perpendicular energy and stimulated ions loss were detected [15]. In this tokamak experiment the LH heating was applied during the neutral beam injection. So, we conclude that the LH heating can also be used for helium ash removal in a stellarator-reactor. The required LH power is estimated to be of the order of 10 MW.

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