EFFECT OF THE LOWER HYBRID HEATING ON THE CONFINEMENT OF HIGH ENERGY IONS IN STELLARATORS

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In a stellarator-type device, the effect of the lower hybrid (LH) heating on the ion confinement is investigated. For this purpose, the motion of high energy ions is simulated numerically in the Large Helical Device, as an example of such a device. It is shown that owing to LH heating, initially well-confined particles are expelled from the plasma in time less then the ion-electron collisional time. Therefore, it is possible to use this method of heating for helium ash removal in a stellarator-reactor.

PACS: 52.55.Hc

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 time. The Large Helical Device [1] (LHD) with the magnetic axis shifted inwardly with respect to the geometrical center is an example of such a configuration with an improved particle confinement [2,3]. As the simulation of a single particle motion shows, in such a configuration the high energy ion confinement time (t_{ic}) exceeds significantly the ion-electron collisional time [2,3] $\tau_E^{i/e}$. Besides, the confinement of high energy ions in the core region depends weakly on the particle pitch value λ at the start point (here $\lambda = V_{\|}/V$ with $V_{\|}$ being the parallel velocity of the particle motion along the magnetic field lines, and V the full particle velocity) (see Fig.1). From the tokamak experiments (see, for example, [4,5] it is well known that at the lower hybrid (LH) heating of tokamak plasmas, the regime of ion stochastic heating [6,7] 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) get the perpendicular kinetic energy. Keeping in mind the weak dependence of t_{ic} on λ, it is interesting to clarify the following question: whether the LH heating could affect the high energy ion confinement in a stellarator. 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 center 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 center motion because of a space change in both the LH wave amplitude and conditions of the wave-particle interaction.

It is known that the drift approximation is valid for description of charged particle motion in stellarators, if the magnetic field variations in space and time are small within the Larmor radius $\rho_L = V_\perp / \omega_c$ and the Larmor period $T_L = 2\pi / \omega_c$ ($\omega_c = eB_0/mc$ is the cyclotron frequency). The heliotron configuration, as considered in the paper, is characterized by comparatively large value of $B_0 = 3T$ and a small value of the inverse aspect ratio (a_p/R=0.16). In such a configuration, drift approximation can be used even for fast particles with energies $W > 100$ keV.

In heliotrons, the representation of the magnitude of the magnetic field along a field line requires the following expansion in a Fourier series:

$$B/B_0 = \sum_{j=0}^{\infty} \sum_{N=-\infty}^{\infty} \varepsilon_{j,N}(r) \cos(j\theta - NM\phi). \tag{1}$$

Here r, θ and ϕ are magnetic coordinates [9], where r is the radial coordinate normalized by the plasma radius a_p and related to the flux surface label as $\psi = B_0 r^2/2$; θ and ϕ are the poloidal and toroidal angle-like variables, respectively; 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. Guiding center motion of a charged particle in heliotrons is described in magnetic coordinates by the following equations [8]:

$$\frac{dr}{dt} = -\frac{V_D}{\varepsilon_t}\frac{\partial b}{\partial \theta}, \quad \frac{d\theta_0}{dt} = \frac{V_D}{\varepsilon_t}\frac{\partial b}{\partial r},$$

$$\frac{dV_{\|}}{dt} = -\omega_c V_D \frac{\partial b}{\partial \phi}, \quad \frac{d\phi}{dt} = \Omega_\phi . \tag{2}$$

Here $b = B/B_0$; $\theta_0 = \theta - \iota\phi$ is the field line label, and the rotational transform ι is related to the poloidal flux $2\pi\psi_p$ and the toroidal flux $2\pi\psi$ as $\iota = -d\psi_p/d\psi$. In Eq. (2), $V_D = V_{\nabla B} + V_{cur}$ is the particle drift velocity due to the gradient−B drift ($V_{\nabla B}$) and the curvature drift (V_{cur}), where $V_{\nabla B} = \mu c/(eR)$, and $V_{cur} = mcV_{\|}^2/(eBR)$, μ is the particle magnetic moment; $\Omega_\phi = V_{\|}/R$ is the toroidal transit frequency. The last closed flux surface was adopted as a loss boundary.

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 heliotron is based on the classical Karney's papers [6,7]. 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, $\nu = \omega/\omega_{ci}$, ω_{ci} is the cyclotron frequency of high energy ions, $r_{LH} = k_\perp V_\perp / \omega_{ci}$. We now assume that the frequency is higher than $\omega_{pI}(0)$ (with $\omega_{pI}(0)$ being the bulk ions plasma frequency at the magnetic axes), thus the LH resonance will not be located in plasma. With a proper choice of the initial value of $N_\parallel$ ($N_\parallel$ is the parallel component of refractive index), the electron Landau damping and bulk ion stochastic heating will be negligibly small [10]. The high energy ions happen to be the only kind of particles which interact with the wave. Using the results of the studies of propagation and absorption of LH waves in stellarators [10] we will approximate the space variation of $N_\parallel$ as follows:

$$N_\parallel = N_{\parallel 0}(1 + C_1 b) \quad . \tag{5}$$

where $N_{\parallel 0}$ and C_1 are constants. We put $|\varepsilon_3/\varepsilon_1| \approx m_I/m_e \cdot \omega^2_{pI}(r) / (\omega^2 - \omega^2_{pI}(r))$ (m_e and m_I are the electron and bulk ion mass), $N_\perp \approx \sqrt{|\varepsilon_3/\varepsilon_1|} N_\parallel$. Since $E_\perp \approx N_\perp E_\parallel / N_\parallel >> E_\parallel$, then $E_0 \approx E_\perp$. Thus, E_0 varies when the interacting ion moves along its trajectory.

Because of assuming the density of high energy ions 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. Owing to the dependence of the wave parameters on both space coordinates and change in $V_\perp$ at the motion of ion guiding center, the interaction conditions (3) and (4) will vary from point to point. Defining the phase of wave-ion interaction as $\varphi = (\omega - k_\parallel V_\parallel)t + \varphi_0$ (with φ_0 being the initial random phase) we write the difference equation in the form:

$$r^{i+1}_{LH} = r^i_{LH} + \frac{\nu}{r_{LH}} A\cos(\varphi^i)\cos\left[(r^2_{LH} - \nu^2)^{1/2} - \nu \arccos\frac{\nu}{r_{LH}} - \frac{\pi}{4}\right], \tag{6}$$

$$t^{i+1} = t^i - \frac{\sqrt{r^2_{LH} - \nu^2}}{r^2_{LH}} A\cos(\varphi^i)\cos\left[(r^2_{LH} - \nu^2)^{1/2} - \nu \arccos\frac{\nu}{r_{LH}} - \frac{\pi}{4}\right]. \tag{7}$$

where A is directly related to α.

For the beginning let us consider the high energy ion motion in the LHD magnetic field when the wave-particle interaction is absent. As an example we calculate the trace of the passing ion with energy $W = 100\,keV$ and pitch $\lambda = 0.6$. The coordinates of the ion starting position are $r = a_p/2$, $\theta_0 = \pi/6$, $\phi_0 = 0$ (Figs. 2, 3). When starting outside the torus and moving counterclockwise, this passing particle is well confined. When collisions are neglected, the ion confinement time exceeds considerably the ion-electron collisional time $\tau^{i/e}_E$.

Now we will study the motion of ions affected by LH heating. For plasma and LH wave parameters we put $n_I(0) = 10^{14}\,cm^{-3}$, $\omega/\omega_{pI}(0) = 1.85$, $\nu(0) = 55.17$, $N_{\parallel 0}$=2.1, C_1=0.7. The initial amplitude of the wave is taken so that at $r = 0$ we have $\alpha = \alpha_{min}$. This corresponds to $E_0 = 12\,kV/cm$ at $r = 0$. The ion position at the start and its pitch are identical to the case when rf is turned off. As the Figs. 4,5 show the ion left the plasma volume in time less then $\tau^{i/e}_E$. The principal wave-ion interaction occurs at the initial and final parts of the ion trajectory. There is no interaction during the time interval not shown in Fig.5. The process of the change in the ion kinetic energy is rather complicated. The initial part of the trace is shown in Fig.6 in more detail. This period of motion consists of 235 cyclotron periods. When the ion is moving in the heliotron confining field, the kinetic energy getting intermits by energy loss or energy conserving (like from 7 μs to 9 μs). Since $V_\perp$ is the only component of the particle velocity, that changes its value during heating, the main effect of heating on guiding center motion is consisted in the change of the particle pitch (see Fig.7, in which the pitch value, as rf is turned off, is shown for comparison). The radial component is the main part of both $N_\perp$ and $E_\perp$ [10]. Therefore, a shift of the particle guiding center (directed in $E_\perp \times B$) occurs mostly in the poloidal direction. Its value is negligibly small. When the LH power increases, the time of the ion expulsion becomes shorter (Figs. 8,9), but the kinetic energy increment is increased.

Thus, while simulating the motion of the high energy ions that initially occupied the region of the "absolute confinement" in a heliotron, we reveal that these ions can be expelled from plasma by the LH heating. By making the proper choice of the wave frequency and initial $N_\parallel$ spectrum, it is possible to provide the wave damping due to the high energy ions only without disturbing the bulk plasma ions and electrons. Let us refer to the tokamak experiment [11]. In this experiment the LH heating was applied during the neutral beam injection (NBI). The growth of ions perpendicular energy and stimulated ions loss were detected. So, we conclude that the LH heating can be also used for helium ash removal in a heliotron-reactor. Now this problem is under discussion for tokamaks [12,13], but it is also an important question for heliotrons and stellarators. While applying this concept to a Heliotron reactor requires detailed simulation of the expelled particles motion outside the last closed flux surface. The ion energy of 100 *keV*, taken in our simulations as an example, is close to the energy of NB injected ions in LHD [14]. Thus, it is possible to check the method suggested in the paper, performing the proper experiment in this heliotron. Being performed, this experiment should be accompanied by the calculations of the antenna spectrum, the LH wave propagation and absorption and the estimation of the required power.

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FIGURES

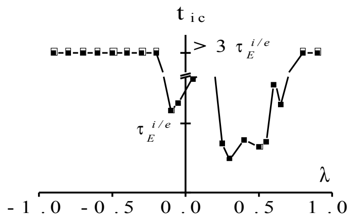

Fig.1. A variation of the particle confinement time t_{ic} via pitch. The start point $r=a_p/2$, $\theta_0=\pi/6$, $\phi_0=0$

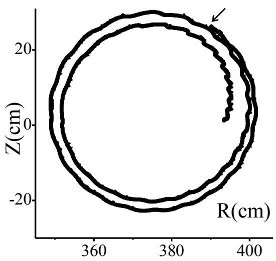

Fig.2. The absolutely confined passing ion orbit, started (arrow) from the outside of the torus with $r=a_p/2$, $\theta_0=\pi/6$, $\phi_0=0$ and $\lambda=0.6$ is shown. Here the distance from trace to magnetic axis (Z=0 cm, R=375 cm) corresponds to current average radius of flux surface. The rf heating is turned off. The particle drift is directed inside the initial flux surface

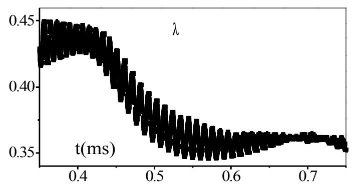

Fig.3. A variation of the pitch λ via time is shown during a drift for the passing particle orbit (Fig.2)

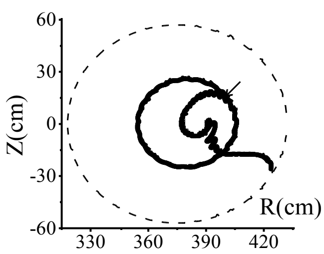

Fig.4. As in Fig. 2, but rf is turned on. The particle becomes trapped in the helical ripple well, which leads to the change in the direction of the particle drift and its escape from the plasma

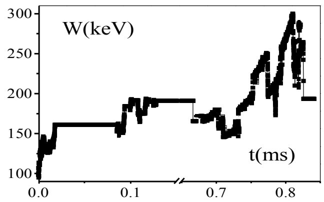

Fig.5. A variation of W via time is shown during a drift for the particle orbit presented in Fig.4

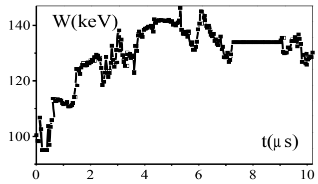

Fig.6. A variation of W via time is shown in more detail for the initial part of trace presented in Fig.4

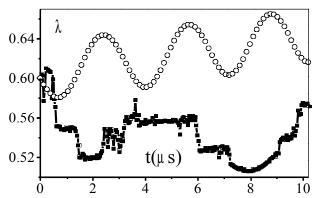

Fig.7. A variation of the pitch λ via time is shown for the same period as in Fig.6. The squares correspond to rf is turned and open circles relate to rf is turned off

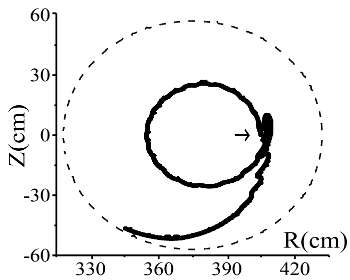

Fig.8. As in Fig.4, but LH wave amplitude is doubled

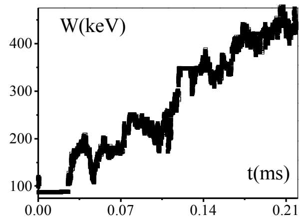

Fig.9. A variation of W via time is shown during a drift for the particle orbit presented in Fig.8