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Possible Experiments with K⁺ Ions on Large Helical Device to Simulate Alpha Particle Behavior

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Abstract

New experiments are proposed with the K^+ ions on Large Helical Device to simulate the behavior of alpha particles in fusion reactors. Some important physics issues: the penetration of the ions injected outside the last closed magnetic surface into the core of the plasma confinement volume if they have the transition orbits in order to control the electric field in plasma, the study of the cold alpha-particles removal, the removal of the impurity ions from the confinement volume, – can be checked experimentally. Here one experiment to study loss cone transit particles is proposed.

Keywords:

ion transportation, alpha particle simulation, loss cone, transit orbit

1. Introduction

Experiments with K^+ ions on Large Helical Device with the reduced magnetic field can simulate the behavior of hot alpha particles in fusion reactors because of the similarity of the Larmor radius to plasma minor radius ratios [1].

One of the possible experiments on LHD is proposed here. The injection of K^+ ions outside the last closed magnetic surface can be carried out in such way that the ion penetrates into the core of the confinement volume. This is the way to check the fundamental idea [2,3] to use the particles with the transit orbits, which belong to helical ripple loss cone for the penetration into the helical device. This effect when the helically trapped particle becomes the blocked particle can be used to control the electric field in plasma [3]. The reverse effect when the blocked particle becomes the helically trapped one can be helpful to remove the impurity ions or "cold" alpha particles from the center of the confinement volume to outside.

2. Main Equations and Magnetic Field Model

2.1 Main equations

For our consideration guiding center equations are used [4]

$$\frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}t} = V_{\parallel}\frac{\boldsymbol{B}}{B} + \frac{c}{B^2}[\boldsymbol{E} \times \boldsymbol{B}] + \frac{M_j c\left(2V_{\parallel}^2 + V_{\perp}^2\right)}{2e_j B^3}[\boldsymbol{B} \times \nabla B],$$

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$$\frac{\mathrm{d}W}{\mathrm{d}t} = eE\,\frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}t} + \frac{M_j\,V_\perp^2}{2B}\,\frac{\partial B}{\partial t}\,,$$

$$\frac{\mathrm{d}\mu}{\mathrm{d}t} = 0\,. \qquad (2.1)$$

Here $\boldsymbol{r}$ is the radius-vector of the particle trajectory, $\boldsymbol{B}$ is the magnetic field, $\boldsymbol{E}$ is the electric field, $V_\parallel$ and $V_\perp$ are the parallel and the perpendicular velocities, M_j and e_j are the mass and charge of the particle, W is the kinetic energy and μ is the magnetic moment of the particle

$$\left(\mu = \frac{M_j\,V_\perp^2}{2B}\right).$$

2.2 Main magnetic field

The main magnetic field ($\mathbf{B} = \nabla\Phi$) is modeled with the use of the magnetic field potential

$$\Phi = B_0\left[R\varphi - \frac{R}{m}\sum_n \varepsilon_{n,m}(r/a_h)^n \sin(n\vartheta - m\varphi) + \varepsilon_{1,0}\,r\sin\vartheta\right], \qquad (2.2)$$

where B_0 is the magnetic field at the circular axis, R and a_h are the major and minor radii of the helical winding; r,ϑ,φ are the coordinates connected with the circular axis of the torus, r is the radial variable, ϑ and φ are the angular variables along the minor and major circumference of the torus, ϑ increases in the direction opposite to the main normal of the circular axis of the torus; metric coefficients are the following: $h_r = 1$, $h_\vartheta = r$, $h_\varphi = R + r\cos\vartheta$; m is the number of the magnetic field periods along the torus, l is the helical winding pole number. The index n assumes the values $n = l,\ l-1,\ l+1$; $\varepsilon_{n,m}$ are the coefficients of the harmonics of the magnetic field.

For the results presented in Section 4 the parameters of the Large Helical Device [5] are taken as follows: $l = 2$, $m = 10$, $B_0 = 1.5$ T, $R = 390$ cm, $a_h = 97.5$ cm; the values of $\varepsilon_{n,m}$ are taken in such a way that the magnetic surfaces, the magnetic field modulation along the force line and other properties coincide with the results of Ref. [6]. For the configuration with the inward shift of the magnetic axis the parameters are $\varepsilon_{2,10} = 0.79$, $\varepsilon_{3,10} = -0.032$, $\varepsilon_{1,10} = -0.056$ and $\varepsilon_{1,0} = 0.045$.

3. Properties of Ion Transit Orbit

The particle starts its motion as the blocked one then crosses the transition curve and becomes the helically trapped one. The trajectory of the particle in the blocked state and then in the state of the helically trapped can be described with the equations $J_\parallel(r,\vartheta,V_\parallel/V) = const$, where $J_\parallel = \oint J_\parallel\,dl$ is the longitudinal adiabatic invariant of the particle in the corresponding state [2].

The starting points (with the coordinates r_0,ϑ_0) of particles, which start outside the last closed magnetic surface, cross the transition curve (at the point with coordinates r_t,ϑ_t) and should penetrate into the core of confinement volume (to the point with the coordinates r_c,ϑ_c), can be found from the system of equations

$$J_{\parallel\,\mathrm{hel.tr}}(r_0,\vartheta_0,V_\parallel/V) = J_{\parallel\,\mathrm{hel.tr}}(r_t,\vartheta_t,V_\parallel/V)\,, \qquad (3.1)$$

$$J_{\parallel\,\mathrm{blocked}}(r_t,\vartheta_t,V_\parallel/V) = J_{\parallel\,\mathrm{blocked}}(r_c,\vartheta_c,V_\parallel/V)\,, \qquad (3.2)$$

$$2 = 1 + \frac{V^2 - \mu B_0 + \mu B_0\left(r_t/R\right)\cos\vartheta_t}{\mu B_0\,\varepsilon_{l,m}\left(A^2 + B^2\right)^{1/2}}\,, \qquad (3.3)$$

where

$$A = \sum_n \frac{\varepsilon_{n,m}}{\varepsilon_{l,m}}\sin n\vartheta_t\,,$$
$$B = \sum_n \frac{\varepsilon_{n,m}}{\varepsilon_{l,m}}\cos n\vartheta_t\,, \qquad (3.4)$$

We can use the configurations with the different sets of parameters. The sets of parameters with the different signs and values of the coefficients before the harmonics of the angular variables are responsible for the shift of the magnetic axis (outward or inward), the shape of the magnetic surfaces and the modulation of the magnetic field absolute value along the magnetic field line.

4. Penetration of Potassium Ions in the Center of the Confinement Volume

In this paper we concentrated on the study of the K^+ ions in the inward shifted magnetic configuration. As the test particle the K^+ ion with the energy $W = 1$ keV is taken. One typical trajectory of the transit particle is shown on Figs. 1 (vertical cross-section) and 2 (horizontal cross-section). The starting points are found here with the rule of the orbit reversal. Under the starting point coordinates $r_0 = 60.537$ cm, $\vartheta_0 = 0.1251$ rad, $\varphi_0 = 1.035$ rad, $V_\parallel/V = -0.4$ the test ion starts as the helically trapped particle and then becomes the blocked one and stays as the blocked one during the time $\tau_{\mathrm{blocked}} = 6$ ms. The period of the particle staying in the blocked state can be seen on Fig. 3. The 3-D trajectory of such test ion is seen on Fig. 4. One can see the parts of the trajectory when the test ion is the helically trapped one and when it becomes the blocked (toroidally trapped) one.

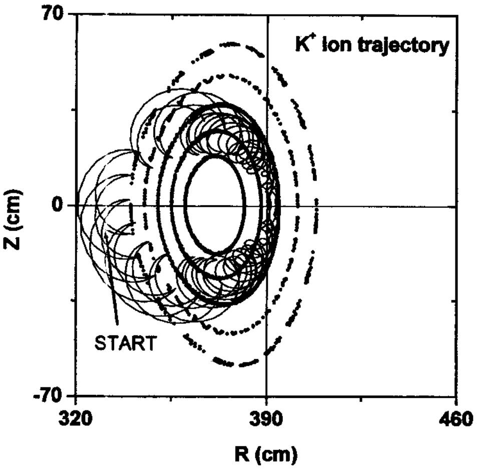

Fig. 1 Vertical projection of the test ion trajectory on the background of the magnetic surfaces

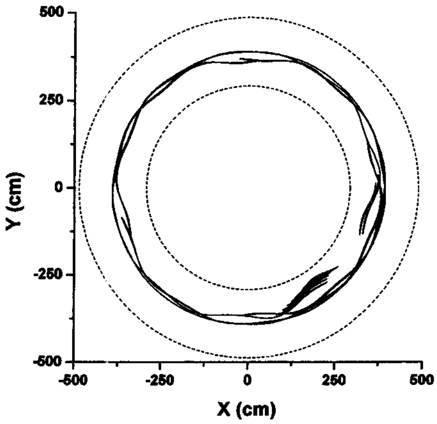

Fig. 2 Horizontal projection of the test ion trajectory

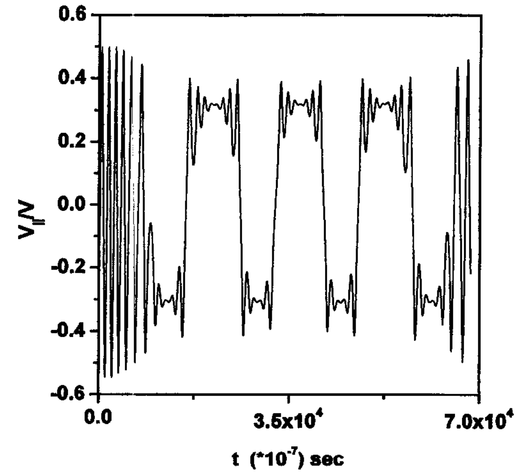

Fig. 3 Variation of the parallel velocity of the test ion as a function of time

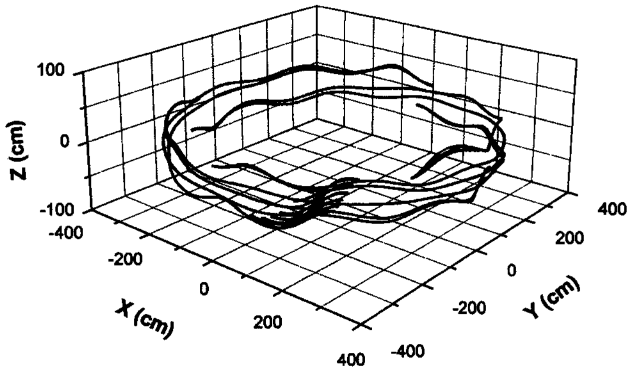

Fig. 4 3-D trajectory of the test ion

5. Discussion

The described effect – the penetration of the ions injected outside the last closed magnetic surface into the core of the confinement volume, can be reversed. It means that the impurity ions with transit orbits (cold alpha particles, particularly) can be removed from the core of the confinement volume to the periphery of plasma.

6. Conclusions

With the use of K^+ ion gun it is possible to carry out the experiment for the study of the penetration of injected ions, which belong to the helical ripple loss cone into the helical device. This is one of the possible experiments to simulate the alpha-particle behavior.

The starting points are outside the last closed magnetic surfaces. The starting points can be chosen in such way that it is suitable to place the ion gun.

This experiment can be carried out in the vacuum configuration and can open the way for the experimental study other physics effects such as estafette of resonances [7] for the removal of the test particle.

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