DRIFT RESONANCE AND PARTICLE REMOVAL FROM HELICAL PLASMA

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The effect of magnetic field perturbation on motion of deuterium, tritium and helium ions is studied theoretically and by numerical simulation of the charged particle motion in electromagnetic field. A method for alpha-particles (fusion reaction product) removal from plasma in helical device due to drift resonance formation is proposed. The point is that helium ion escapes from the confinement volume due to the natural drift in inhomogeneous magnetic field.

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INTRODUCTION

The present work is concentrated on studying the cold alpha-particles removal [1-3], that is applicable only in a helical magnetic field device and exploits the advantages of torsatron-heliotron devices.

This paper is focused on analysis of the helium ash removal from the helical reactor. Magnetic field modulation on the inner magnetic surfaces is favourable for particle drift reduction, while magnetic field modulation on the outer surfaces is unfavourable. The proposed method consists of drift island formation for the selected ions and subsequent delivery the ions (due to drift island motion) from inner magnetic surfaces to the outer ones at the periphery of the confinement volume. Drift island motion to the periphery of the confinement volume is implemented by slow changing of current in additional coils (e.g. local island divertor coils in LHD). The motion of the drift island transports the ions to the periphery of the confinement volume, where they move outwards due to natural drift in inhomogeneous magnetic field. This procees is possible in torsatron only, where the magnetic field modulation varies along the minor radius. The sketch of the removal process is presented in the Fig. 1.

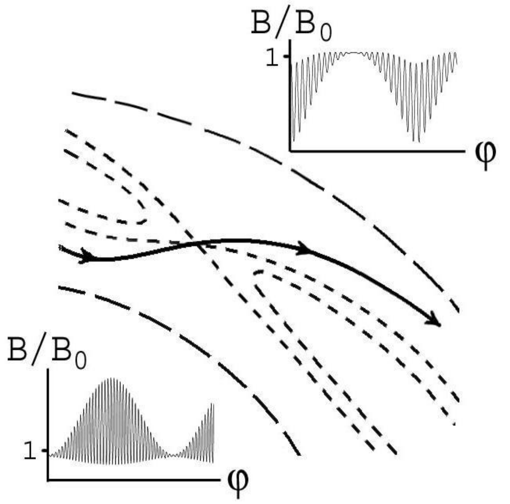

Fig. 1. Removal process sketch

1. DRIFT RESONANCE AND DRIFT ISLAND MOTION

Drift resonance can be obtained by introducing of the magnetic field perturbation. This can be implemented on the Large Helical Device (LHD) by means of additional local island divertor (LID) coils. It is possible to shift the drift island across the magnetic surfaces to the periphery of the confinement volume by changing the current in the vertical magnetic field coils in time [4-7].

1.1. BASIC EQUATIONS

The ion trajectories are modelled by numerical integration of the the guiding center equations [8]:

$$\frac{d\mathbf{r}}{dt} = v_{\parallel}\frac{\mathbf{B}}{B} + \frac{c}{B^2}[\mathbf{E},\mathbf{B}] + \frac{Mc\left(2v_{\parallel}^2 + v_{\perp}^2\right)}{2B^3 Ze}[\mathbf{B},\nabla B];\quad(1)$$

$$\frac{dW}{dt} = Ze\mathbf{E}\frac{dr}{dt} + \frac{Mv_{\perp}^2}{2B}\frac{\partial B}{\partial t}; \qquad (2)$$

$$\frac{d\mu}{dt} = 0, \qquad (3)$$

where $\mathbf{r}$ is the guiding center radius-vector of the particle with the charge Ze and mass M, which moves in the magnetic field **B**, the electric field **E;** and $\mu = Mv_{\perp}^2/2B$ is the magnetic moment of the particle.

1.2. MAGNETIC FIELD MODEL

Main magnetic field ($\mathbf{B} = \nabla\Phi$) is modelled with the use of magnetic field potential:

$$\Phi = B_0\left[R\varphi - \frac{R}{m}\sum_n \varepsilon_{n,m}\left(\frac{r}{a}\right)^n \sin(n\vartheta - m\varphi) + \varepsilon_{1,0} r\sin\vartheta\right]. \quad (4)$$

The parameters of the Large Helical Device chosen for further simulations are [9]: l=2, m=10, B_0=3 T, R=390 cm, a=97.5 cm. The values of amplitudes $\varepsilon_{n,m}$ of magnetic field harmonics simulate the outward shifted magnetic configuration: $\varepsilon_{2,10}$=0.76, $\varepsilon_{3,10}$=0.032, $\varepsilon_{1,10}$=-0.056, $\varepsilon_{1,0}$=0.007. Vertical cross-sections of the magnetic surfaces are presented in the Fig. 2.

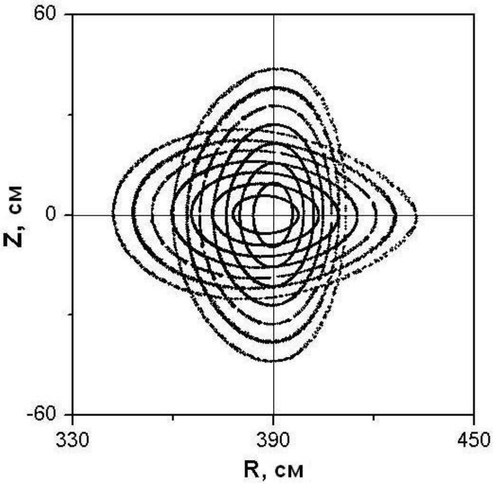

Fig. 2. Magnetic configuration

Perturbing magnetic field is modelled with the use of the scalar potential:

$$\Phi_p = B_0 a_h \frac{\varepsilon_{m,n,p}}{m_p} (r / a_h)^{m_p} \sin(m_p \vartheta - n_p \varphi + \delta_{m,n,p}) \,. \quad (5)$$

The perturbing magnetic field wave numbers, amplitude and phase values are taken as follows: m_p=2, n_p=1, $\varepsilon_{2,1,p}$=0.0005, $\delta_{2,1,p}$=π/2. Technical availability of such a perturbation with the use of Local Island Divertor coils in LHD is taken into consideration.

1.3. DRIFT SURFACES OF ${}^2_1D$, ${}^3_1T$ AND ${}^4_2He$ IONS IN LHD GEOMETRY

The particles which are trapped on the helical inhomogeneity move to the periphery of the confinement volume due to the natural drift. Passing particles remain in the central part of the confinement volume. Typical trajectories of the ${}^4_2He$, ${}^2_1D$ и ${}^3_1T$ in the presence of the perturbation are presented on the Figs. 3-5. Start positions and start parameters are the same for all the particles. Start velocity pitch is $v_\parallel / v \approx 0.7$.

1.4. ANALYSIS OF RESONANT CONDITION ι*=n/m

Drift rotational angle of a particle in the inhomogeneous electromagnetic field can be described as [10]:

$$\iota^* = \iota_B + \overset{*}{\iota}_{\mathbf{E}\times\mathbf{B}} + \overset{*}{\iota}_{\mathbf{B}\times\nabla B} \,, \quad (6)$$

here $\overset{*}{\iota}_{\mathbf{B}}$ is magnetic field rotational transform angle, $\overset{*}{\iota}_{\mathbf{E}\times\mathbf{B}}$ and $\overset{*}{\iota}_{\mathbf{B}\times\nabla B}$ are drift terms of the particle rotation angle, which are derived from the drift terms in Eq.(1):

$$\iota_B = \frac{1}{2}\frac{m}{l}\varepsilon_{l,m}^2 \left(\left(\frac{Rl}{ma}\right)^4 \left(\frac{r_0}{a}\right)^{2l-4} + \left(\frac{Rl}{ma}\right)^2 \left(\frac{r_0}{a}\right)^{2l-2} \right); \quad (7)$$

$$\overset{*}{\iota}_{\mathbf{E}\times\mathbf{B}} = \frac{c}{v_\parallel} \frac{(-1)\Phi_0}{B_0 a} \frac{k_E}{\Psi(a_{pl})} \left(A - \frac{\Psi}{\Psi(a_{pl})} \right)^{k_E - 1} \frac{R}{a} \,; \quad (8)$$

$$\overset{*}{\iota}_{\mathbf{B}\times\nabla B} = \frac{\left(2v_\parallel^2 + v_\perp^2\right)}{2\omega_C} \frac{1}{v_\parallel a} \frac{R}{a} \left(\left(\frac{a}{R}\right)^2 - \varepsilon_{l,m}^2 l \left(\frac{r_0}{a}\right)^{2l-2} \right). \quad (9)$$

Terms in (6) for the particles with the same energy and velocity pitch $v_\parallel/v$, but with mass numbers M_1 and M_2 and with the charge numbers Z_1 and Z_2 can be compared in such a way:
for *gradient B* drift term

$$\frac{\overset{*}{\iota}_{\mathbf{B}\times\nabla B1}}{\overset{*}{\iota}_{\mathbf{B}\times\nabla B2}} = \frac{Z_1}{Z_2}\sqrt{\frac{M_1}{M_2}} \,, \quad (10)$$

for drift in *crossed electromagnetic field* term

$$\frac{\overset{*}{\iota}_{\mathbf{E}\times\mathbf{B}1}}{\overset{*}{\iota}_{\mathbf{E}\times\mathbf{B}2}} = \sqrt{\frac{M_1}{M_2}} \,. \quad (11)$$

One can see the difference in dependence of the terms (10) and (11) on M and Z. This means that if the drift resonance ι*=*n/m* takes place for the ${}^4_2He$ ion, it does not take place for ${}^2_1D$ and ${}^3_1T$ ions.

Additional numerical simulations show that resonance condition does not take place for deuterium and tritium ions with the energy of 1.5- and 2-times higher than that of the alpha-particle. In that case the drift island does not arise for fuel ions and they cannot be removed along with the cold alpha-particles from the confinement volume using this method. The trajectories of these ions are fairly the same as those, presented in the Figs. 4 and 5.

Similar numerical simulations are carried out for deuterium and tritium ions with energy (temperature) values, which were measured in D-T plasma in JET experiments. Result shows that drift island formation for cold alpha-particles and its removal do not influence the D-T fuel injection and heating.

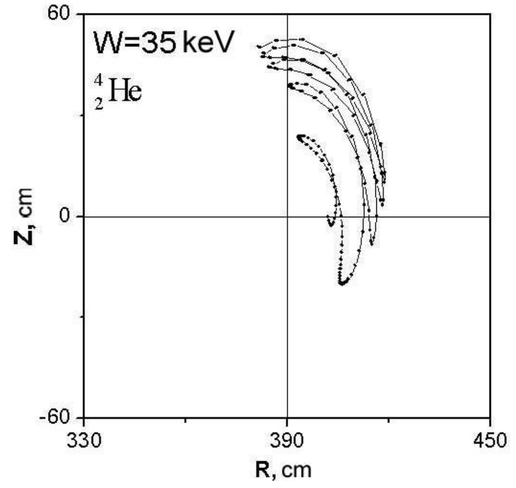

Fig. 3. ${}^4_2He$ ion trajectory

The selectivity of the method is estimated by the range of the alpha-particle energy and velocity pitch values at which the forming of the drift island takes place. Numerical simulations are carried out for the wide range of particle energies and pitch angles. The “successful” range, when the cold alpha-particle removal occurs, is shown in the Fig. 6 in black.

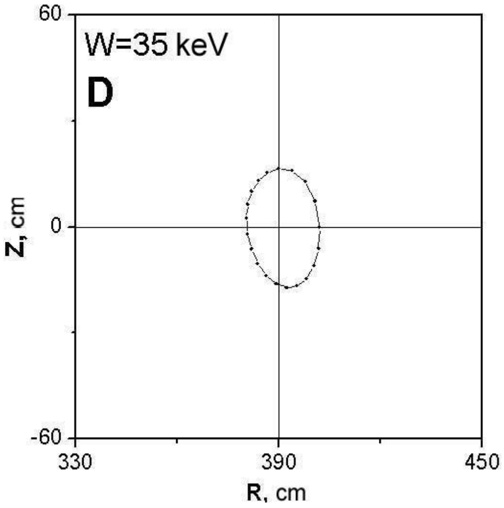

Fig. 4. $^{2}_{1}D$ *ion trajectory*

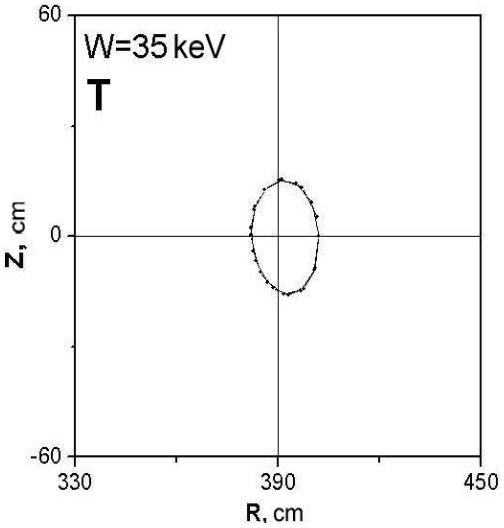

Fig. 5. $^{3}_{1}T$ *ion trajectory*

2. DISCUSSIONS

The resonance and the formation of the drift island take place for the particle with the certain drift rotation angle ι^*. The expression (6) for the drift rotation angle consists of three terms. One of the terms depends on magnetic configuration parameters. Two of them depend on particle energy (velocity), mass and charge. Each term depends on different set of parameters, and these parameters contribute to each term in different manner. It is possible to vary parameters in such a way that the value of a single term remains the same, e.g. for the particle with *Ze/m*, which is 1.5 times less, and with energy, which is 1.5 times higher. But at the same time, the contribution of the other term that depends only on particle mass, alters. As a result, the total drift rotation angle – the sum of three terms – alters. So, the resonance condition does not occur and thus, the particle is not removed from the plasma. This suggests a quite narrow selectivity of the proposed method.

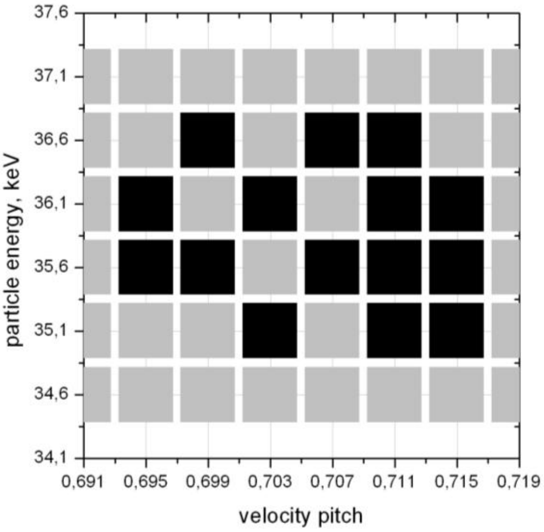

Fig. 6. Removed particle parameters

CONCLUSIONS

- A new method of cold (35 keV) alpha-particles removal is proposed. The method exploits the drift island motion and subsequent particle trapping and escaping from the confinement volume.
- Numerical simulations of the described perturbation are carried out for the wide range of particle energies and pitch-angles. The results show that $^{2}_{1}D$ and $^{3}_{1}T$ ions of the fusion fuel do not form the drift island and do not escape from the plasma core.
- The motion of the charged particles in stellarator magnetic configuration with the resonant magnetic perturbation is studied numerically. The possibility of the selective cold alpha-particle removal from the plasma is shown on the base of analysis of the particle trajectories in wide range of energies and pitch-angles.

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ДРЕЙФОВЫЙ РЕЗОНАНС И ВЫВОД ЧАСТИЦ ИЗ ПЛАЗМЫ СТЕЛЛАРАТОРА

А. Антуфьев, И. Павленко, И. Гирка

Теоретически и с помощью численного моделирования движения заряженных частиц в электромагнитном поле изучено влияние возмущения магнитного поля на движение ионов дейтерия, трития и гелия. Предложен метод удаления альфа-частиц (продуктов реакции синтеза) из плазмы винтовой ловушки с помощью формирования дрейфового острова. Основной особенностью является то, что ион гелия уходит из объёма удержания благодаря естественному дрейфу в неоднородном магнитном поле.

ДРЕЙФОВИЙ РЕЗОНАНС ТА ВИДАЛЕННЯ ЧАСТИНОК З ПЛАЗМИ СТЕЛАРАТОРА

О. Антуф'єв, І. Павленко, І. Гірка

Теоретично та за допомогою числового моделювання руху заряджених частинок в електромагнітному полі вивчено вплив збурення магнітного поля на рух іонів дейтерію, тритію та гелію. Запропоновано метод видалення альфа-частинок (продуктів реакції синтезу) з плазми гвинтового пристрою за допомогою формування дрейфового острова. Головною особливістю є те, що іон гелію виходить з об'єму утримання завдяки природньому дрейфу в неоднорідному магнітному полі.