CONTROL OF α -PARTICLE CONFINEMENT IN THE HELICAL DEVICE FOR FUSION WITH "MAGNETIC AXIS SWEEPING"

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We examine here the possibility to control the α -particle confinement where α -particles appear as the products of the $D+{}^3_2He$ fusion in the experiment on Large Helical Device /LHD/. We study here the specific for the torsatron / heliotron device method, namely the control of the torsatron / heliotron magnetic configuration and confinement properties with the use of the poloidal field (PF) coils. The proposed here method can be used in DEMO–grade helical reactor Force Free Helical Reactor /FFHR/.

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1. INTRODUCTION

For the successful operation of the steady state fusion reactor it is necessary to provide the confinement of hot α -particles and the transfer of their energy to the background plasma ions (new portions of fuel ions) and then the removal of the cooled α -particles (helium ash). The observation on tokamaks JET and TFTR has shown that the transport of α -particles in experiments with $D+T$ mixture is close to neoclassical one and there is the transfer of the energy from the fusion products to electrons of plasma [1-3]. However, there remains the problem of cold α -particles accumulation in fusion reactor which leads to the strong bremsstrahlung. This problem can be solved in the helical devices because of the in-homogeneity of the helical magnetic field in the outer half of the plasma cross-section. The same feature what can be helpful for the removal of cold α -particles at the same time can be dangerous for the confinement of hot α -particles. It is possible to organize the so called drift resonances for α -particles with the energy in some interval of values and remove the α -particles selectively [4]. There is one approach more, namely the shifting of the magnetic axis which can be the sequence of at least two mechanisms: the increase of beta causes the shift of the magnetic axis, the change of magnetic surface shape and the magnetic field modulation. The last characteristic is important for the confinement of the helically trapped and passing particles. It is possible to control the currents in the PF coils and to improve the plasma equilibrium state and change the confinement of particles. This control is named as the magnetic axis sweeping [5, 6].

There exists the possibility to observe the fusion products in experiments with $D+{}^3_2He$ in helical fusion plasma and to study α -particles confinement, particularly, the specific for helical device possibility to remove cold α -particles with the use of PF coils current variation. Namely Large Helical Device (Fig.1), where the helical field can be changed (varied) in time with the use of poloidal field (PF) coils, is the most appropriate installation for the observation of the α -particles.

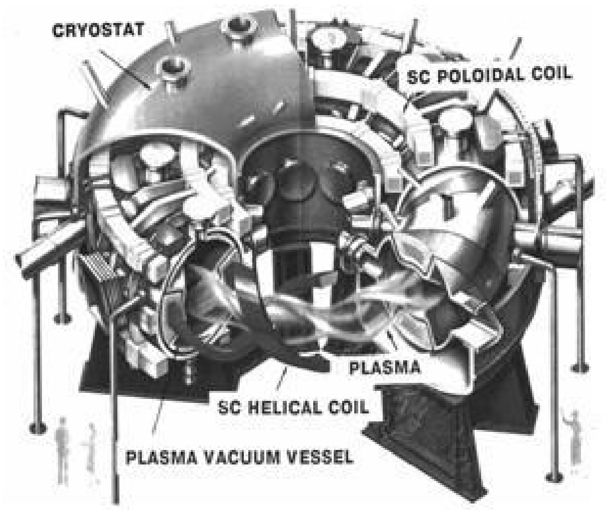

Fig.1. Schematic view of the helical field (HF) coils, poloidal field (PF) coils

In our previous paper [4] we have proposed to improve the FFHR-type DEMO relevant reactor design with the additional winding of poloidal field coils type. These coils should supply independently on the main inner vertical (IV) and outer vertical (OV) PF coils. The currents in the additional coils may be 100 times smaller than in the main PF coils. These additional coils create the perturbation magnetic fields which produce the drift resonances of the ions which should be removed. Drift resonances can be very effective method to remove the passing particles. The helically trapped particles can drift out due to the motion in the helical field. The method can be especially effective if we combine two mechanisms**:** magnetic axis sweeping (magnetic axis oscillation under the variation of currents in poloidal field coils) and drift resonances at the plasma edge**.**

2. REMOVAL OF THE COLD α -PARTICLES

2.1. MAGNETIC SURFACES AND MAGNETIC FIELD MODULATION

As we know that when α -particles appear then β , where $\beta = 8\pi\left(n_e T_e + n_i T_i + n_\alpha T_\alpha\right)/B_0^2$, increases, the magnetic field $B_\perp^\beta \approx \dfrac{\beta}{4}\dfrac{B_0}{\iota(a_{pl})}$. The poloidal coils (IV and OV) also contributes in the magnetic field $B_\perp^{OV+IV}$.

Under the effect of this total field $B_\perp^\beta + B_\perp^{OV+IV}$ the magnetic configuration is shifted outward. In such way we change the configuration from drift optimized one to another one – with so called B/B_0 modulation-unfavorable for the confinement of helically trapped particles, i.e. with stronger drift of helically trapped particles. Magnetic surfaces are shifted, their radius is reduced. Small magnetic islands appear at the periphery of confinement volume (Fig.2).

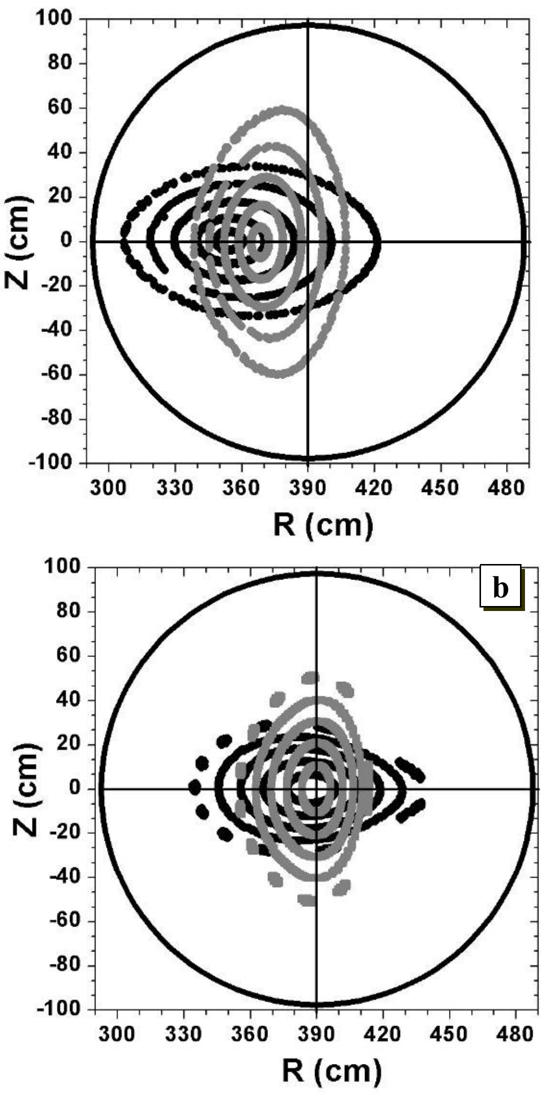

Fig.2. Change of the magnetic surfaces under the $B_\perp^\beta + B_\perp^{OV+IV}$ effect: vacuum magnetic surfaces (a) and magnetic surfaces under $B_\perp^\beta + B_\perp^{OV+IV}$ (b)

The modulation of the magnetic field along the field line affects strongly on the trapped and passing particle motion.

In these two configurations the modulation of the magnetic field along the field lines change in the corresponding way (Fig.3).

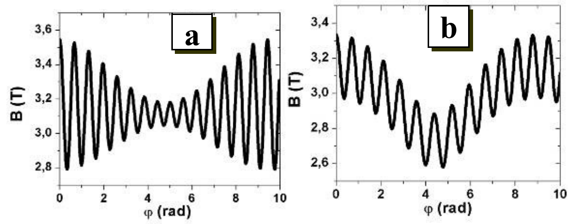

Fig.3. Change of the magnetic field modulation B/B_0 along the field line from the vacuum case (a) to the case under the $B_\perp^\beta + B_\perp^{OV+IV}$ effect (b)

2.2. TRAPPED AND PASSING PARTICLE TRAJECTORIES

The favorable / unfavorable character of the modulation of the magnetic field demonstrates itself on the trapped particle trajectories (Fig.4).

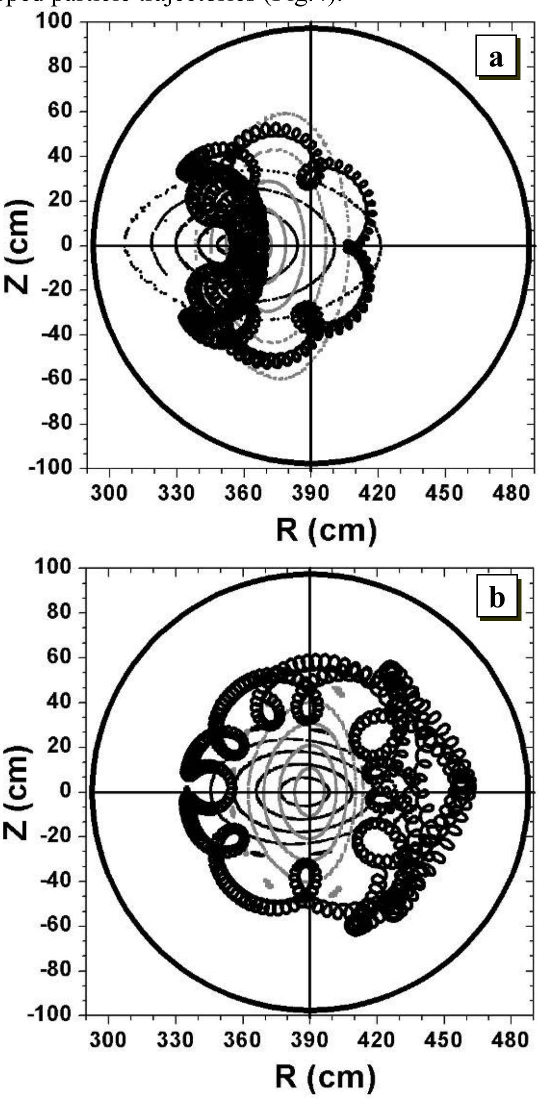

Fig.4. Trapped cold α -particle ($W = 367$ keV, $V_\parallel / V = 0.3$) trajectories in configurations: vacuum (a) and under $B_\perp^\beta + B_\perp^{OV+IV}$ effect (b)

Similar effect of the increase drift deviation also takes place for the passing particles (Fig.5). Here each trajectory is shown as complete one. The projections of the particle trajectories on the vertical cross-section of torus in the initial (vacuum) configuration and under $B_{\perp}^{\beta} + B_{\perp}^{OV+IV}$ effect are shown on Fig.6.

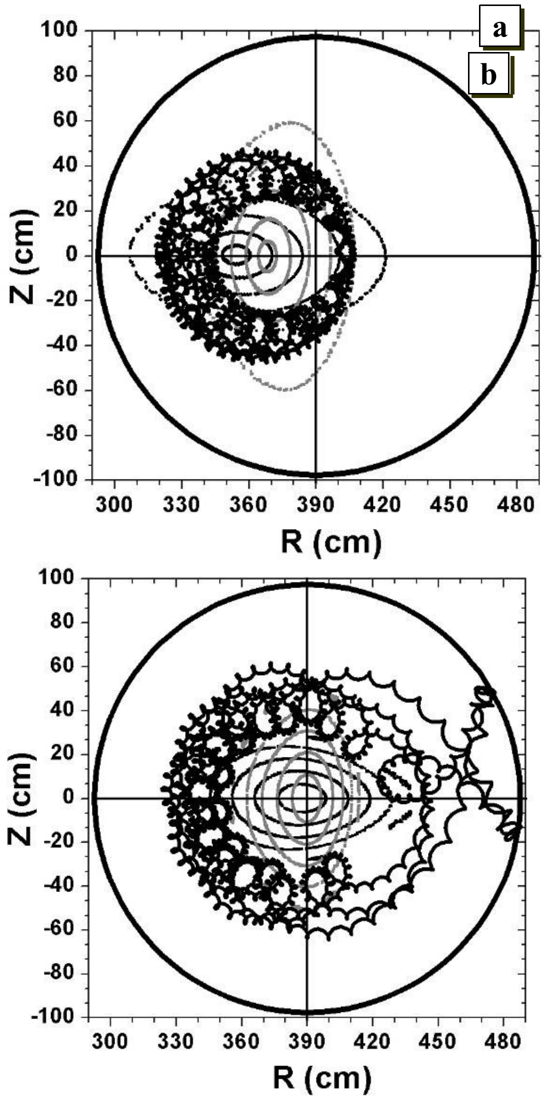

Fig.5. Passing cold α -particles (W = 367 keV, $V_{\|}/V$ =0.9) trajectories in the configurations: vacuum (a) and under $B_{\perp}^{\beta} + B_{\perp}^{OV+IV}$ effect (b)

The footprints of the passing cold α -particles form the regular drift surfaces The projections of the drift surfaces, which are shown on Fig.6,a in one vertical cross-section of the torus on the background of the vacuum magnetic surfaces, differ from the magnetic surface but not so strongly as in the case of the magnetic surfaces perturbed with the total magnetic field $B_{\perp}^{\beta} + B_{\perp}^{OV+IV}$ (Fig.6,b). In the last case we see the "destructive" tendency in the behavior of the footprints of the drift trajectory. There is also the penetration of the particle across the magnetic islands especially near X-points. We should note that there are X-points of the magnetic surfaces and X-points of the drift surfaces. The difference between them is very important: if the electrons can move closer to the magnetic field lines the energetic ions will deviate strongly from the magnetic surfaces. In the real plasma this difference is controlled with the establishing of the ambipolar electric field. The escape of the particles (ions, especially and α -particles particularly) affects noticeably on the structure of the radial electric field E_r at the plasma edge.

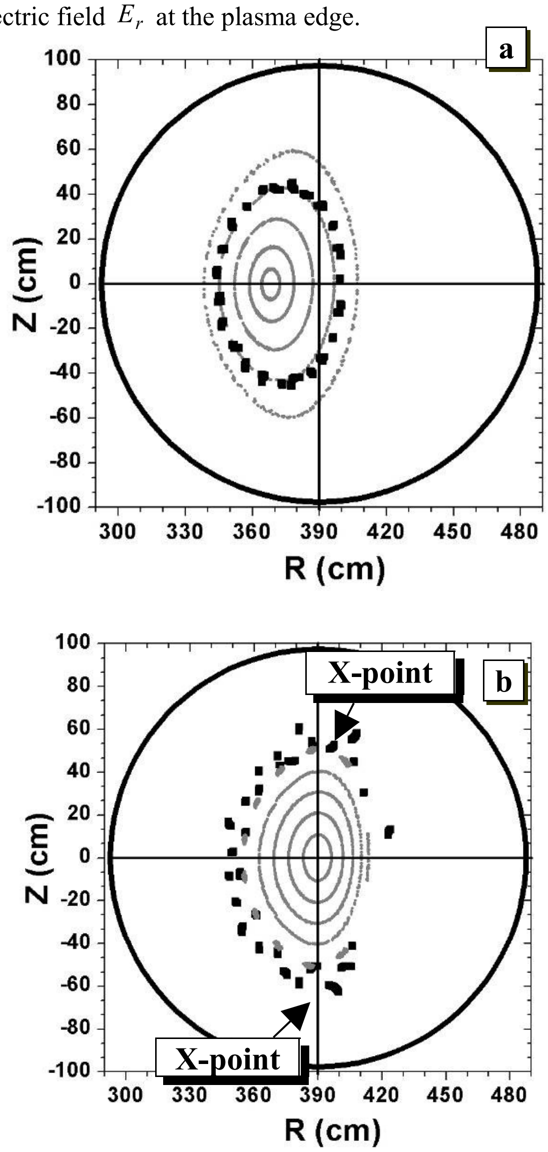

Fig.6. Projection (on one vertical cross-section of the torus) of trajectories of cold α -particles with the parameters from Fig.5

The drift surface X-points which we see in one vertical cross section (with vertically oriented magnetic surfaces as the background (Fig.6,b) also present in all other vertical cross-sections of the torus and, particularly, with horizontally oriented magnetic surfaces. It means that the place of the escape of the particles (location of the particle escapes) now becomes known. This knowledge is useful the diverting plasma purposes.

2.3. ANALYSIS OF X-POINTS IN MAGNETIC AND DRIFT SURFACES

The tool used here for the study is the analysis of drift separatrix which helps us to find the space in the r, ϑ, φ where the particles leave the confinement volume. The structure of the drift separatrix on the background of the magnetic separatrix shows us the deviation of the ***drift*** X-points ***from magnetic*** X-points (Fig.7).

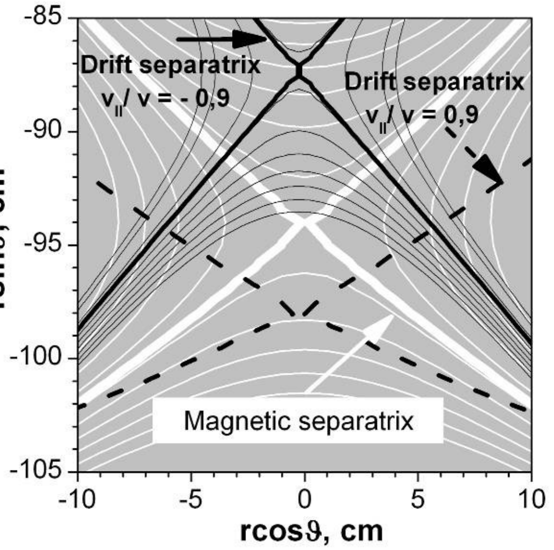

Fig.7. Parts of magnetic and drift surfaces, the magnetic separatrix and drift separatrixes for the α particles with the energy $W = 3670\, keV$ and pitch-velocity $V_{\|}/V = \pm\ 0.9$

The families of the magnetic and drift surfaces are obtained from the first integral of the guiding center equations (drift trajectories) which are presented below for the case of the exact helical symmetry [7]

$$\psi^{*} = b_0 \frac{\alpha r^2}{2} - r \sum_n b_n I_n'(n\alpha r)\cos(n\theta) + \frac{mcV_{\|}}{eB}\left(B_z + \alpha r B_{\vartheta}\right),$$

where

$$B_r = \sum_n n b_n I_n'(n\alpha r)\sin(n\theta),$$

$$B_{\vartheta} = \sum_n n \frac{b_n}{\alpha r} I_n(n\alpha r)\cos(n\theta),$$

$$B_z = b_0 - \sum_n n b_n I_n(n\alpha r)\cos(n\theta),$$

and $b_0 = \dfrac{2lJ_{hel}\alpha}{c}$, $b_n = 2ab_0\alpha K_n'(n\alpha a)$.

Here summation is being carried out n, where $n = l * j$ and $j = 1,2,3...$ .The drift surfaces are obtained under the parameters: $W_{\alpha} = 3670$ keV; $\frac{V_{\|}}{V}$ =0,9; the current in the helical field (HF) coils I_{HF} =5.6 MA.

Analytical connections between the change of PF coil currents, i.e. $\Delta I_{IV}(t)/I_{HF}$ and $\Delta I_{OV}(t)/I_{HF}$ with the amplitudes b_{m_k,n_k} and "wave" numbers m_k, n_k of harmonics of the magnetic field perturbations are described in [4]. There also the analytical expressions which connect the confinement times of plasma particles τ_p, α -particles τ_{α} and energy confinement time τ_E with the transport coefficients for the trapped particles $D_{\perp} \propto 1/\nu$ (ν is the collision frequency) and $D_{\perp\, stochastic} \propto b_{m,n}^2$ for the resonance passing particles.

Here we would like to point the time characteristic for the ***magnetic axis sweeping.***

3. WHAT IS THE MAGNETIC AXIS SWEEPING

The difference between the techniques proposed in [4] and proposed in this paper is in the following. Earlier there is proposed to excite the drift resonances for the passing cold α -particles at the plasma edge (where the drift rotational transform cold α -particles $\iota^{*} = m/n$) and use the overlapping of the adjacent drift resonances for the stochastic transport of the particles (which should be removed) to provide the escape of these particles. This transport is selective relatively the energy of the particles. To realize this effect we had proposed [4] to add the poloidal field (PF) coils with the special attached coils with the currents 100 smaller than in the main PF coils.

Magnetic axis sweeping is the same as magnetic axis shift oscillations in time. These oscillations (with the characteristic time period near 100…150 seconds) are realized with the controllable variation of the current values in the poloidal field coils. During these oscillations the magnetic surfaces are shifted in the direction "inward - outward - inward", change their cross-section shape and correspondingly their confinement properties. In the ***outward*** shifted magnetic configuration the confinement of the particles is worse than in the ***inward*** shifted magnetic configuration. However, this feature (properties of the confinement) is selective relatively the particle energy. That is why it possible to confine the hot α -particles, to remove the cold α -particles and do not deteriorate the confinement of the background ions.

We have discussed here only the part of scenario which can be studied on Large Helical Device in experiments with $D + {}^3_2He$. The further development of this concept of the removal of cold α -particles and /or the helium ash will be presented in further papers.

CONCLUSIONS

1. Extraction of the "cold" α -particles (${}^4_2He$ with the energy 10 times smaller than the birth energy, i.e. $W = 367$ keV) which can be obtained in the possible experiments with the mixture $D + {}^3_2He$ on Large Helical Device is considered in this paper. The techniques discussed here is different from studied earlier [4]. In the previous case the magnetic field perturbations were used. In this paper the removal of cold α -particles with the magnetic axis sweeping is proposed. This mechanism uses the specific for the helical device advantages, namely the transform of the magnetic configuration.

2. This study can be used for DEMO relevant reactor of the helical type Force Free Helical Reactor /FFHR/ [8]. FFHR should operate with $D + T$ and the reduction of the cold α -particles fraction is also very important. The design of FFHR, which now includes two kinds of the coils: helical field (HF) coils and two pairs of the poloidal field (PF) coils, can be added with the small current perturbation coils [4]. It would be helpful for the suppression of the MHD activity in the fusion plasma

and effective for the controlling the cold α -particles fluxes at the plasma edge.

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РЕГУЛИРОВАНИЕ УДЕРЖАНИЯ α -ЧАСТИЦ В ТЕРМОЯДЕРНОЙ ЛОВУШКЕ С ВИНТОВЫМИ МАГНИТНЫМИ ПОЛЯМИ С ПРИМЕНЕНИЕМ «ОСЦИЛЛЯЦИИ МАГНИТНОЙ ОСИ»

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Рассматривается возможность регулирования удержания α -частиц, которые могут появиться как продукты синтеза $D+{}^3_2He$, в экспериментах на Large Helical Device /LHD/. Изучается специфический для торсатрона / гелиотрона подход, а именно, регулирование конфигурации и удерживающих свойств с использованием магнитных полей от обмоток полоидального магнитного поля. Предложенный метод может быть использован для термоядерного реактора градации DEMO-реактора с винтовыми магнитными полями Force Free Helical Reactor /FFHR/.

РЕГУЛЮВАННЯ УТРИМАННЯ α -ЧАСТИНОК У ТЕРМОЯДЕРНІЙ ПАСТЦІ З ГВИНТОВИМИ МАГНІТНИМИ ПОЛЯМИ З ВИКОРИСТАННЯМ «ОСЦИЛЛЯЦІЇ МАГНИТНОЇ ВІССІ»

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Розглядається можливість регулювання утримання α -частинок, які можуть з'явитися у результаті синтезу $D+{}^3_2He$, в експериментах на Large Helical Device /LHD/. Вивчається специфічний для торсатрону / геліотрону підхід , а саме, регулювання конфігурації та утримуючих властивостей з використанням магнітного полю від обмоток полоїдального магнітного полю. Запропонований метод можна використовувати у термоядерному реакторі градації DEMO-реактор з гвинтовими магнітними полями Force Free