PACS: 28.52.Cx, 52.55.Pi

THE FUSION PRODUCT LOSSES DUE TO RESONANT MAGNETIC PERTURBATIONS IN TOROIDAL PLASMAS

Yu.K. Moskvitina[1,2], **A.O. Moskvitin**[2], **O.A. Shyshkin**[2]
[1,2] National Science Centre "Kharkov Physics and Technology Institute"
Ukraine, Kharkiv, Akademicheskaya St., 1, 61108
[2] V.N. Karazin Kharkiv National University
Ukraine, Kharkiv, Svobody sq., 4, 61022
E-mail: Yu.Moskvitina@gmail.com

Received 09 June 2011

The suppression of edge-localized modes (ELMs) by means of the externally applied resonant magnetic field perturbations (RMPs) and its effect on plasma transport is investigated actively on modern tokamaks. In present paper the modification of loss rates of fusion born alpha particles caused by application of RMPs in tokamak plasma is examined. This study has been performed by means of test-particle simulations. To simplify calculations we use magnetic field model with circular magnetic surfaces. The transport properties of alpha particles are investigated during 3 seconds time interval by tracing the test-particle ensemble. Each particle trajectory is calculated by means of integration of full orbit equations. Three regimes of particle losses are identified during the evolution of the particle ensemble. The formation of magnetic islands together with the stochastic magnetic layers at the plasma edge is the natural consequence of RMPs excitation. It is demonstrated that due to the formation of these resonant magnetic field structures the irregularities of energetic alpha particle orbits occur, and hence the substantial increasing of the losses from the plasma periphery is observed. RMPs slightly affect the first orbit losses of fusion alphas.

KEY WORDS: RMPs, fusion product losses, full orbit, alpha particle.

ПОТЕРИ ПРОДУКТОВ ЯДЕРНОГО СИНТЕЗА В ТОРОИДАЛЬНОЙ ПЛАЗМЕ ОБУСЛОВЛЕННЫЕ РЕЗОНАНСНЫМИ МАГНИТНЫМИ ВОЗМУЩЕНИЯМИ

Ю.К. Москвитина[1,2], **А.А. Москвитин**[2], **О.А. Шишкин**[2]
[1] Национальный научный центр Харьковский физико-технический институт
ул. Академическая, 1, Харьков, Украина, 61108
[2] Харьковский национальный университет имени В.Н. Каразина
пл. Свободы 4, Харьков, Украина, 61022

Подавление гранично-локализованных мод (ELMs) внешними резонансными магнитными возмущениями (RMPs) и их влияние на перенос плазмы активно изучается на современных токамаках. В работе рассматривается изменение скорости потерь термоядерных альфа частиц при наличии RMPs в токамаках. Данное исследование проведено в одночастичном приближении. Для упрощения вычислений в работе используется модель магнитного поля с круглыми магнитными поверхностями. Свойства переноса альфа частиц изучаются путем моделирования движения ансамбля пробных частиц в течение 3 секунд. Траектория каждой частицы рассчитывалась на основании уравнения полной орбиты. При исследовании эволюции ансамбля частиц были выделены 3 режима потерь. Образование магнитных островов со стохастическими слоями на периферии плазмы является естественным следствием использование RMPs. Показано, что образование этих резонансных структур в топологии магнитного поля приводит к нерегулярному поведению орбит энергичных альфа частиц, и, следовательно, наблюдается существенное увеличение потерь этих частиц. RMPs слабо влияют на потери альфа частиц на первой орбите.

КЛЮЧЕВЫЕ СЛОВА: RMPs, потери продуктов синтеза, уравнение полной орбиты, альфа частица.

ВТРАТИ ПРОДУКТІВ ЯДЕРНОГО СИНТЕЗУ В ТОРОЇДНІЙ ПЛАЗМІ ОБУМОВЛЕНІ РЕЗОНАНСНИМИ МАГНІТНИМИ ЗБУРЕННЯМИ

Ю.К. Москвітіна[1,2], **А.О. Москвітін**[2], **О.О. Шишкін**[2]
[1] Національний науковий центр Харківський фізико-технічний інститут
вул. Академічна, 1, Харків, Україна, 61108
[2] Харківський національний університет імені В.Н.Каразіна
пл. Свободи. 4, Харків, Україна, 61022

Послаблення гранично-локалізованих мод (ELMs) зовнішніми резонансними магнітними збуреннями (RMPs) та їх вплив на транспорт плазми активно вивчається на сучасних токамаках. В роботі розглядається зміна швидкості втрат термоядерних альфа частинок за наявності RMPs у токамаках. Дане дослідження проведено в одночастинковому наближенні. Для спрощення розрахунків у роботі використовується модель магнітного поля з круглими магнітними поверхнями. Властивості транспорту альфа частинок вивчаються шляхом моделювання руху ансамблю пробних частинок протягом 3 секунд. Траєкторія кожної частинки розраховувалася на основі рівняння повної орбіти. При дослідженні еволюції ансамблю частинок були виділені 3 режими втрат. Утворення магнітних островів зі стохастичними шарами на периферії плазми є природнім наслідком використання RMPs. Показано, що утворення цих резонансних структур у топології магнітного поля призводить до нерегулярної поведінки орбіт енергійних альфа частинок, і, як наслідок, спостерігається значне підвищення втрат цих частинок. RMPs слабо впливають на втрати альфа частинок на першій орбіті.

КЛЮЧОВІ СЛОВА: RMPs, втрати продуктів синтезу, рівняння повної орбіти, альфа частинка.

The confinement of energetic ions such as fusion produced $\alpha-$particles is essential to maintain burning plasma conditions. Tokamak experiments on charged fusion product confinement and direct loss measurements [1-3] gave rise to intensive theoretical and numerical investigations on $\alpha-$particle behavior in tokamak plasmas. Fast ions play an essential role in the physics of tokamak as they drive a significant part of the processes in magnetic confined plasma [4-6]. On the one hand, fusion born ion energy should be transferred to the background plasma to maintain ignition. On the other hand, cold fusion ions should be removed for radiation energy loss decreasing.

While in many studies the tokamak has been associated with an axisymmetric configuration, the real toroidal magnetic field lines will always exhibit undulations. These undulations can be roughly divided into toroidal and helical perturbations. The toroidal perturbations of magnetic field caused by a discreteness of toroidal field (TF) magnetic coils. TF ripple can result in a significant loss of energetic particles in a tokamak [7-10]. The main causes for helical perturbations are machine error field, externally applied resonant magnetic field perturbations (RMPs) and plasma MHD-instabilities of the same or different helicities. This type of perturbations can result energetic ion losses too [11-14].

For the first time the efficiency of RMPs in suppression of ELMs was demonstrated in DIII-D experiments [15-17]. Further the experiments with RMPs were carried out on tokamaks: JET [18-20], MAST [21], Compass-C [22], TEXTOR [23], NSTX [24], Asdex Upgrade [25] in order to control particle and heat flux at the plasma edge. In addition the recent successful experiments on Type-I ELMs suppression in DIII-D using a radial magnetic perturbation are of great interest for the next-step tokamak ITER [26].

The RMPs become powerful tool for modifying the edge transport properties and for plasma stability control [27-29]. The main aim of proposing ergodization of magnetic fields in tokamaks by RMPs was the distribution of the power to a large fraction of the walls [30]. It is still an issue for large scale steady state fusion devices. But more studying is needed of its effect on charged high-energy fusion product confinement. Especially important this interaction becomes in the modern fusion tokamaks and future reactors. The modification of edge transport properties of fusion products becomes the crucial point for approving the application of RMPs on forthcoming fusion reactors.

The aim of this paper is to study the fusion $\alpha-$particle losses driven by RMPs which are used for mitigation or complete suppression of edge localized modes (ELMs), which are intrinsic instabilities in H-mode plasmas. For this purpose numerical code was developed. This code simulates the dynamics of the particle ensemble. The simulation is based on the test-particle approach. To calculate each particle trajectory the numerical solution of the full orbit equation is carried out by the Runge-Kutta method. Coulomb collisions are taken into account by a 3-dimensional Monte-Carlo operator employing a continuous spectrum of random velocity changes [31].

The paper is organized as follows, in the section MODELS, ASSUMPTIONS AND NUMERICAL PROCEDURES the model of the magnetic configuration, geometrical parameters and plasma parameters used in numerical simulation are presented. The effect of RMPs on particle dynamics is demonstrated with the help of numerical treatment based on solving full orbit equation (Newton-Lorentz equation) in the section NUMERICAL RESULTS. Discussion and conclusions are presented in the section DISCUSSION AND CONCLUSIONS.

MODELS, ASSUMPTIONS AND NUMERICAL PROCEDURES

Ensemble dynamics evaluation

In order to simulate the ensemble dynamics each particle from the ensemble was traced. The trajectories of these particles were calculated from the Newton-Lorentz equation

$$m\ddot{\mathbf{r}} = e\mathbf{E} + \frac{e}{c}\left[\dot{\mathbf{r}}\mathbf{B}\right], \tag{1}$$

where $\mathbf{r}$ is the charged particle radius-vector, m, e are ion mass and charge, c is the light speed in the vacuum, $\mathbf{E}$ and $\mathbf{B}$ are electric and magnetic field vectors. The effect of the electric field is not included in present calculation. This equation was rewritten in the form of the system of ordinary differential equations. The obtained system of equations was solved numerically by Runge-Kutta method. Each trajectory was saved in the separate file. Then the set of these files was proceeded to analyze the ensemble dynamics.

The transport of alpha particles is often calculated with the guiding center approximation, which follows just the center of Larmor motion and treats magnetic moment as constant. The RMPs causes the magnetic field line undulations of about $5cm$ in radial direction that is comparable with Larmor radius of fast ions. These features can break the approximation because of large gradients of the magnetic field strength and large Larmor radii of alpha particles.

Magnetic field model

In the present calculation the quasi-toroidal coordinates (r, ϑ, φ) are used, where r is a radial coordinate; ϑ and φ are the poloidal and toroidal angles, respectively. For reasons of a simpler demonstration the simulation treats alpha particles in tokamaks with circular magnetic flux surfaces. The main magnetic field is introduced in the following form

$$\mathbf{B}^0 = \frac{B_0 R_0}{R}\left\{ 0,\ \frac{r}{R_0}\iota(r),\ 1 \right\}, \tag{2}$$

where B_0 is the magnetic field on-axis of torus, $R = R_0 - r\cos\vartheta$, $R_0 = 296\,cm$ is the major radius of the torus, ι is the rotational transform.

The externally applied resonant magnetic perturbations are written as [32]

$$\mathbf{B}^1 = \frac{B_0 R_0}{R} b_{m,n} \left(\frac{r}{a_c}\right)^{m-1} \left\{ \sin(m\vartheta - n\varphi); \cos(m\vartheta - n\varphi); 0 \right\}, \tag{3}$$

where $b_{m,n}$ is the ratio of the RMPs amplitude to the on-axis magnetic field, a_c is the RMP coil radius, m and n are the poloidal and toroidal numbers of the perturbation field, respectively.

For numerical simulation we used the JET-like magnetic configuration. Parameters of this configuration are $B_0 = 2\cdot 10^4\,\mathrm{Gs}$, $\iota = 0.8 - 0.55(r/a)^2$, and plasma minor radius $a = 120\,cm$.

Parameters of RMPs are the following $b_{mn} = 5\cdot 10^{-4}$, $m = 3$, $n = 1$ and $a_c = 150\,cm$. These values adequately represent experimental ones used for suppression of ELM-activity on JET [21]. The corresponding topology of the magnetic surfaces is presented on Fig. 1. Here the Poincare plot of the regular magnetic surfaces is depicted together with the stochastic magnetic layer on the edge (in gray) and with the isolated magnetic island chains (in black). It should be noted, that magnetic field structure corresponds to that one which is calculated by Nardon et al. in paper [21] in approach of vacuum error field correction coil perturbations and axisymmetric tokamak equilibrium. It should be noted that recently the shielding effect of plasma response currents on magnetic field topology is discussed [33,34]. Account of the tokamak real geometry and plasma response currents is underway now.

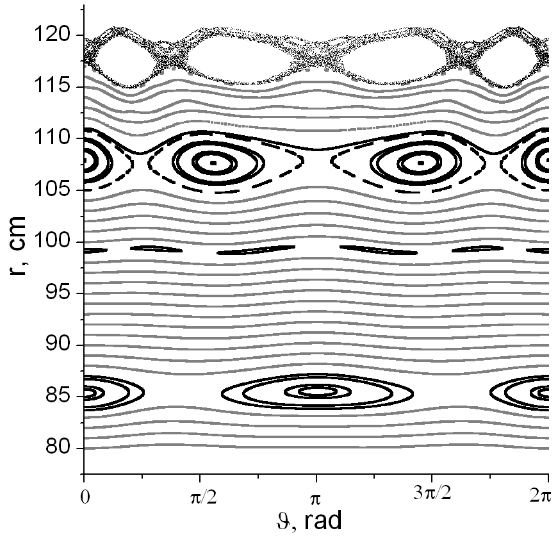

Fig. 1. Tokamak magnetic configuration under resonant magnetic perturbations ($b_{mn} = 5\cdot 10^{-4}$, $m = 3$, $n = 1$)

Monte-Carlo collision operator

Coulomb collisions are taken into account by a 3-dimensional Monte-Carlo operator employing a continuous spectrum of random velocity changes. A test particle changes its velocity components parallel and perpendicular to the magnetic field line from $(\upsilon_\parallel, \upsilon_\perp)$ to $(\upsilon'_\parallel, \upsilon'_\perp)$ by collision with plasma particles, relations among these velocity components are given by [31]

$$\begin{gathered} \upsilon'_\parallel = \upsilon_\parallel + \Delta\upsilon_L \frac{\upsilon_\parallel}{\upsilon} + \Delta\upsilon_T \frac{\upsilon_\perp}{\upsilon}\sin\Omega, \\ \upsilon'_\perp = \left\{ (\upsilon + \Delta\upsilon_L)^2 + \Delta\upsilon_T^2 - (\upsilon'_\parallel)^2 \right\}^{1/2}, \end{gathered} \tag{4}$$

where $\upsilon = \sqrt{\upsilon_\parallel^2 + \upsilon_\perp^2}$ is the total velocity of the test particle, Ω is the Larmor phase, $\Delta\upsilon_L$, $\Delta\upsilon_T$ are the longitudinal and transverse components of the velocity change, respectively. To calculate small random velocity changes due to collisions some assumptions about background plasma should be made. The background plasma consists of 50% mixture of deuterium and tritium ions. The number of electrons satisfies the charge neutrality condition. The plasma component density and temperature radial profiles were chosen in form $n_\beta(r) = n_{\beta 0}\left(1 - (r/a)^8\right)^2$, $T_\beta(r) = T_{\beta 0}\left(1 - (r/a)^2\right)^{0,5}$ where subscript β designates sort of plasma particles $(\beta = e, D, T)$. On-axis electron density is the following $n_{e0} = 10^{14}\,cm^{-3}$ and ion density is $n_{D0} = n_{T0} = 0.5 n_{e0}$. The temperatures on-axis of the all background plasma ions and electrons are assumed to be equal $T_{0\beta} = 10\,keV$. All numerical treatments presented in this paper are performed in assumption of Maxwellian plasma.

NUMERICAL RESULTS

Firstly the dynamics of the fusion born $\alpha-$particles was simulated for two cases: with and without RMPs. In both cases the trajectories of the 400 particles were calculated. It was assumed that $\alpha-$particle is born as a result of deuterium and tritium ions fusion reaction. Thus the initial energy for all particles of the ensemble was $E_0 = 3.5 MeV$. The initial positions of $\alpha -$particles are assumed to be on flux surface near circular axis with $r_0 = 10 cm$. The toroidal and poloidal angles of the start position were generated randomly with uniform distribution. The initial distribution in 3D velocity space was assumed to be isotropic. It should be noted, that initial ensemble for both cases was the same. The trajectory calculation stops either particle reaches plasma boundary $r = 120 cm$ or time exceeds $3.5\,s$.

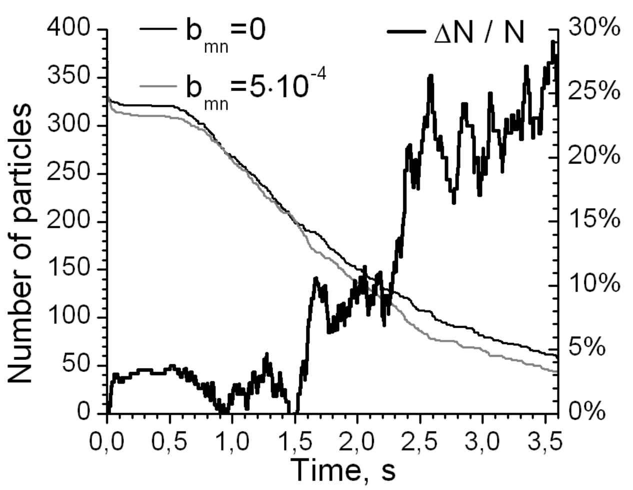

Fig. 2. The density evolution of the $\alpha -$ particle ensemble with initial energy $E_0 = 3.5 MeV$ and birth position $r_0 = 10 cm$ for to cases: with and RMPs

The results of the simulations are presented on the Fig. 2. The density evolution of the $\alpha -$particles ensemble with and without RMPs is shown black line and gray line, respectively. The relative density difference in the referred above cases is indicated by bold black line. The right vertical axis corresponds to the relative density difference.

One can see from Fig. 2 that resonance magnetic perturbations, which are used for ELMs suppression in tokamak, give rise to increased fusion product losses of about 30 %. Besides that in these two cases (with and without RMPs) three transport regimes can be matched. The losses in the first regime were identified as first orbit losses. It was concluded from analyzing the pitch-angle distributions of the lost and confined particles. Besides that sampled trajectories were analyzed. These first orbit losses occur in the first $10 \mu s$ after ensemble born. And we will discuss it in details below. Next regime is characterized by almost lossless ensemble evolution and it lasts till $1 s$. It will be referred in this article as the “plato regime”. And the last regime is characterized by slow losses. It should be noted that the relative density difference achieves its maximum in this regime. The effect of the RMPs on the $\alpha -$particle losses in the first and second regimes doesn’t exceed 2%.

To study the effect of RMPs on the first orbit losses of fusion born $\alpha -$particles, the ensemble dynamics was investigated during the first $10 \mu s$ in details. On this purpose the ensembles containing 1000 particles were considered to improve statistics. The density evolutions of the $\alpha -$particle ensemble under different simulation parameters are shown in the Fig. 3. To compare the effect of RMPs and Coulomb collisions several numerical simulations were carried out using Monte Carlo collision operator. The two different $\alpha -$particle ensembles were used in each numerical simulation:

1) without RMPs, with Coulomb collisions;
2) with RMPs for amplitude $b_{mn}/B_0 = 5 \cdot 10^{-4}$, with Coulomb collisions;
3) with RMPs for amplitude $b_{mn}/B_0 = 50 \cdot 10^{-4}$, with Coulomb collisions;
4) with RMPs for amplitude $b_{mn}/B_0 = 50 \cdot 10^{-4}$, without Coulomb collisions;
5) without RMPs, without Coulomb collisions.

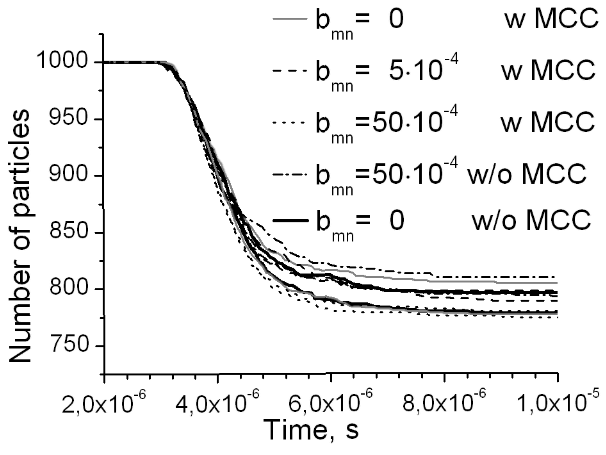

Fig. 3. The density evolution of the $\alpha -$ particle ensemble (first orbit losses) with initial energy $E_0 = 3.5 MeV$ and birth position $r_0 = 10 cm$ under different simulation paramaters shown at plot

As it seen on the Fig. 3 the first orbit losses occur from $3 \mu s$ to $6 \mu s$. For the chosen simulation parameters this time interval corresponds to $50 T_{c\alpha}$, where $T_{c\alpha}$ is the cyclotron period of the $\alpha -$particle. Besides that it is clearly seen that the effect of RMPs on first orbit losses is insignificant and doesn’t exceed 2%. Coulomb collisions do not effect the particle trajectories on present time scale as well. The differences between densities at the end of evolution are caused by the initial distributions of $\alpha -$particle ensemble in the velocity space.

The same investigation was carried out for proton ensemble. The density evolutions for the both alphas and protons are shown in Fig. 4. It should be noted, that for this numerical simulation the protons with initial energy

$E_0 = 14.7MeV$ which are born in $D - {}^3He$ fusion reaction, were used. These protons can be used for diagnostics. From this figure it is seen that quantity of the $\alpha-$particle first orbit losses is about 20%, and quantity of the proton first orbit losses is about 70%. The developed approach for the description of the fast ions dynamics can be used for interpretation of experimental data on fast ion first orbit losses. The $\alpha-$particle first orbit losses occur from $100T_{cp}$ to $150T_{cp}$, i.e. during $50T_{cp}$. While the proton first orbit losses occur from $10T_{cp}$ to $30T_{cp}$, i.e. during $20T_{cp}$.

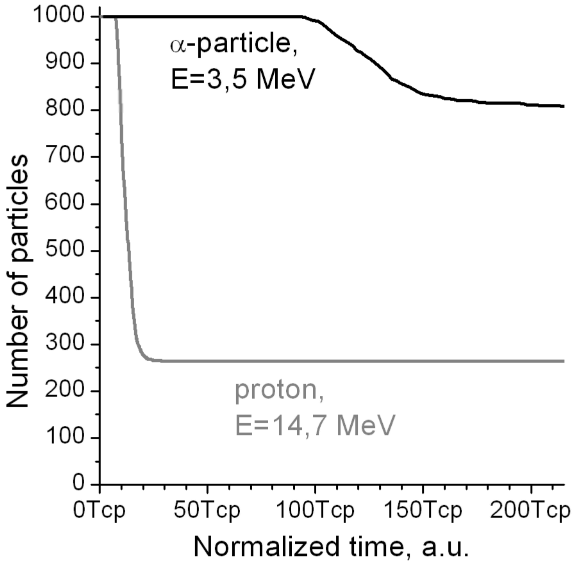

Fig. 4. The density evolution of the $\alpha-$particle ensemble with initial energy $E_0 = 3.5MeV$ and proton ensemble with initial energy $E_0 = 14.7MeV$ (first orbit losses)

After the first orbit losses the rest of the particles drift towards the plasma periphery due to Coulomb collisions. This drift is referred above as ‘plato’ regime. This period lasts for about 1 second, and at the end of it the remaining particles have the energy less than $70keV$. The detailed investigation of third regime which follows the “plato” regime is underway now.

DISCUSSION AND CONCLUSIONS

Agitating the confining magnetic field by resonant magnetic perturbations (RMPs) is a modern method to control the plasma edge transport. RMPs are used for suppression of edge-localized modes (ELM) in tokamaks. Modelling of particle motion that covers a broad particle energy range is an important approach that should clarify the key aspects of the experimental observations with RMPs. The application of RMPs in future devices such as ITER requires an understanding of the perturbed magnetic structure and the correlated modification of transport.

In present paper the evolution of alpha-particle losses due to RMPs is studied by means of test-particle approach. The significance of the performed simulations is the integration of the full orbit equations and good conservation of motion invariants is observed during the tracing time about 3 seconds. This time is long enough to draw out the main conclusions about the loss rates of alphas.

Numerical simulations of the fusion born $\alpha-$particles ensemble dynamics have shown that

- Three main transport regimes are identified during the evolution of the ensemble: first orbit losses, “plato” regime and slow losses (Fig. 2);
- The most significant effect of the RMPs is observed on the slow losses, i.e. RMP losses. The ensemble relative density difference reaches the value of about 30 % under RMPs application for this regime;
- It is demonstrated that RMPs affect only slightly the first orbit losses of fusion alphas. Trajectories of the energetic particles were traced during 10 microseconds in magnetic configurations with and without RMPs.

It should be noted that the first orbit losses of fusion ions occur during first $10\mu s$ after birth. This time interval is small for the slowing down and scattering on electrons and on ions. As it was demonstrated in this paper the effect of RMPs on the first orbit losses of the fusion born $\alpha-$particles is insignificant and doesn’t exceed 2%.

REFERENCES

1. Yu. Baranov, I. Jenkins, V. Kiptily et al. Evidence of anomalous losses of fusion products on JET // 37th EPS Conference on Plasma Physics, Dublin, Ireland, June 21-25. – 2010. – P5.141.10.
2. V.G. Kiptily, C.P. Perezvon Thun, S.D. Pinches et al. Recent Progress in fast ion studies on JET // Nuclear Fusion. – 2009. – Vol.49, № 6. – P. 065030.
3. S.J. Zweben, R.V. Budny, D.S. Darrow et.al. Alpha particle physics experiments in the Tokamak Fusion Test Reactor // Nuclear Fusion. – 2000. – Vol.40, № 1. – P. 91-148.
4. Kolesnichenko Ya.I. The role of alpha particles in a tokamak reactor // Nuclear Fusion. – 1980. – Vol.20, № 6. – P. 727-780.
5. Putvinski S.V. Physics of Energetic Particles in ITER // Nuclear Fusion. – 1998. – Vol.38, № 9. – P. 1275-1281.
6. A. Fasoli, C. Gormenzano, H.L. Berk et al. Chapter 5: Physics of Energetic Ions // Nuclear Fusion. – 2007. – Vol.47, № 6. – P. S264-S284.
7. Yushmanov P.N. // Reviews of Plasma Physics (Edited by M. A. Leontovich, Published by Consultants Bureau New York, London). – 1987. – Vol 16. – P. 117-191.
8. V.A. Yavorskij, Zh.N. Andrushchenko, J.W Edenstrasser, V.Ya. Goloborod’ko Tokamak with weak toroidal field ripples // Physics of Plasmas. – 1999. – Vol.6, № 10. – P. 3853-3867.
9. H. Mimata, K. Tani, H. Tsutsui et. al. Numerical Study of the Ripple Resonance Diffusion of Alpha Particles in Tokamaks //

Plasma and Fusion Research. – 2009. – Vol.4. – P. 008 (1-8).
10. V.O. Yavorskij, Yu.K. Moskvitina, A.A. Moskvitin et al. 3D Fokker-Planck description of TF ripple induced collisional transport of fast ions in tokamaks // – Nuclear Fusion. – 2010. – Vol.50, № 8. – P. 084022 (1-7).
11. A.A. Shishkin, I.N. Sidorenko, H. Wobig Magnetic Islands and Drift Surface Resonances in Helias Configurations // Journal of Plasma and Fusion Research SERIES. – 1998. – Vol.1. – P. 480-483.
12. A.A. Shishkin, A. Sagara, O. Motojima et al. Controlling the cross-field flux of cold α-particles with resonant magnetic perturbations in a helical fusion plasma device // – Nuclear Fusion. – 2007. – Vol.47, № 8. – P. 800-808.
13. Q. Yu, S. Gunter Effect of resonant magnetic perturbations on particle confinement // Nuclear Fusion. – 2009. – Vol.49, № 6. – P. 1-5.
14. Moskvitina Yu.K., A.A. Shishkin Resonant interaction between fusion products and magnetic field perturbation in toroidal magnetic trap with the rotational transform // Problems of Atomic Science and Technology, Series “Plasma Electronics and New Methods of Acceleration”. – 2008. – Vol.6, № 4. – P. 104-108.
15. T.E. Evans, R.A. Moyer, P.R. Thomas et al. Suppression of Large Edge-Localized Modes in High-Confinement DIII-D Plasmas with a Stochastic Magnetic Boundary // Physical Review Letters. – 2004. – Vol.92, № 23. –P. 235003 (1-4).
16. T.E. Evans, R.A. Moyer, J.G. Watkins et al. Suppression of large edge localized modes with edge resonant magnetic fields in high confinement DIII-D plasmas // Nuclear Fusion. – 2005. – Vol.45, № 7. – P. 595-607.
17. T.E. Evans, R.A. Moyer, K.H. Burrell et al. Edge stability and transport control with resonant magnetic perturbations in collisionless tokamak plasmas // Nature Physics. – 2006. – Vol. 2. – P. 419-423.
18. Y. Liang, H.R. Koslowski, P.R. Thomas et al. Active control of type-I edge localized modes on JET // Plasma Physics and Controlled Fusion. – 2007. – Vol.49, № 12B. – P. B581–B589.
19. Y. Liang, S. Jachmich, H.R. Koslowski et al.Active control of edge localized modes with a low *n* perturbation fields in the JET tokamak // Journal of Nuclear Materials. – 2009. – Vol.390-391. – P. 733-739.
20. Y. Liang, H.R. Koslowski, P.R. Thomas et al. Active control of type-I edge localized modes with $n=1$ and $n=2$ fields on JET // Nuclear Fusion. – 2010. – Vol.50, № 2. – P. 025013 (1-11).
21. E. Nardon, A. Kirk, N.Ben Ayed et al. ELM control by resonant magnetic perturbations on JET and MAST // Journal of Nuclear Materials. – 2009. – Vol.390-391. – P. 773-776.
22. P. Cahyna, M. Bécoulet, R. Pánek et al. Resonant magnetic perturbations and edge ergodization on the COMPASS tokamak // Plasma Physics Reports. – 2008. – Vol. 34, № 9. – P. 746-749.
23. O. Schmitz, J.W. Coenen, Frerichs al. Particle confinement control with resonant magnetic perturbations at TEXTOR // Journal of Nuclear Materials. – 2009. – Vol.390-391. – P. 330-334.
24. J.M. Canik, R. Maingi, T.E. Evans et al. ELM destabilization by externally applied non-axisymmetric magnetic perturbations in NSTX // Nuclear Fusion. – 2010. – Vol.50, № 3. – P. 034012 (1-8).
25. W. Suttrop, O. Gruber**,** S. Günter et al. In-vessel saddle coils for MHD control in ASDEX Upgrade // Fusion Engineering and Design. – 2009. – Vol.84, Issue 2-6. – P. 290-294.
26. O. Schmitz, T.E. Evans, M.E. Fenstermacher et al. Aspects of three dimensional transport for ELM control experiments in ITER-similar shape plasmas at low collisionality in DIII-D // Plasma Physics and Controlled Fusion. – 2008. – Vol.50, № 12. – P. 124029 (1-19).
27. H.E. Munick, N. Pomphrey Frequency sweeping: a new technique for energy-selective transport // Nuclear Fusion. – 1994. – Vol.34, № 9. – P. 1277-1282.
28. A. Shishkin Estafette of drift resonances, stochasticity and control of particle motion in a toroidal magnetic trap // Nuclear Fusion. – 2002. – Vol.42, № 3. – P. 344-353.
29. G. Park, C.S. Chang, I. Joseph, R.A. Moyer Plasma transport in stochastic magnetic field caused by vacuum resonant magnetic perturbations at diverted tokamak edge // Physics of Plasmas. – 2010. – Vol.17, № 10. – P. 102503.
30. K.H. Finken, B. Unterberg, Y.Xu et al. Influence of the dynamic ergodic divertor on transport properties in TEXTOR // Nuclear Fusion. – 2007. – Vol.47, № 7. – P. 522-534.
31. K. Tani, M. Azumi, H. Kishimoto, S. Tamura Effect of Toroidal Field Ripple on Fast Ion Behavior in a Tokamak // J. Phys. Society of Japan. – 1981. – Vol.50, № 5. – P. 1726-1737.
32. Yu.K. Moskvitina, A.A. Shishkin Effect of the resonance phenomena on high energetic particle losses in closed magnetic trap with the rotational transform of the magnetic field // Problems of Atomic Science and Technology, Series “Plasma Physics”. – 2008. – Vol.14, № 6. – P. 19-21.
33. M.F. Heyn, I.B. Ivanov, S.V. Kasilov et al. Kinetic estimate of the shielding of resonant magnetic field perturbations by the plasma in DIII-D // Nuclear Fusion. – 2008. – Vol.48, № 2. – P. 024005 (1-14).
34. I.M. Pankratov, A.Ya. Omelchenko and V.V. Olshansky Toroidal consideration of plasma response to penetration of an external low frequency helical perturbation into a tokamak edge plasma // Nuclear Fusion. – 2006. – Vol.46, № 4. – P. S170-S174.