EDGE MAGNETIC ISLAND EXCITATION IN THE U-2M TORSATRON

V.G. Kotenko, V.E. Moiseenko

Institute of Plasma Physics of the NSC KIPT, Kharkov, Ukraine

In the article, via numerical calculations a possibility of magnetic island structure excitation on the edge of closed magnetic surface configuration in a torsatron with the additional toroidal magnetic field coils is shown. The applied scheme to realize the structure is founded on a particular shunting of electrical current in one of the coils. The calculations were carried out taking into account the geometry of the torsatron U-2M functional magnetic system.

PACS: 52.55.Hc

INTRODUCTION

Excited and controlled from the outside magnetic islands near the edge of plasma column in tokamaks and stellarators are presently recognized as one of the effective tools exerting an impact on the plasma MHD-activity [1-6]. Also they can promote helium ash evacuation from the fusion reactor hot zone [7] and have an appreciable effects on the conditions of runaway electron flow formation [8] and on the fast ion loss level [9, 10].

The magnetic island excitation is put into effect by application of a relatively low value of perturbing magnetic field on the main magnetic field. Usually the planned magnetic field perturbation is produced using the coils having a special shape which can be placed outside or inside the vacuum chamber of the device.

In the present paper a possibility of magnetic island structure formation nearby the last closed magnetic surface in the U-2M plasma device,-a torsatron with additional toroidal magnetic field coils,-is investigated via numerical calculations. In the torsatron the magnetic field is perturbed by shunting a part of the electric current in one of these coils.

1. INITIAL MAGNETIC SURFACE CONFIGURATION

The torsatron U-2M magnetic system [11] is the basis of the calculation model. The main geometrical characteristics of the magnetic system are the following:

- the toroidicity a/R_0=0.2618, a is the minor radius of the torus (average radius of helical coils), R_0 is the major radius of the torus. All over the text the lengths are expressed in R_o units;
- the number of helical coils l=2;
- the number of helical coil pitches m_h=2.

Fig. 1 schematically represents the torsatron U-2M magnetic system calculation model [12].

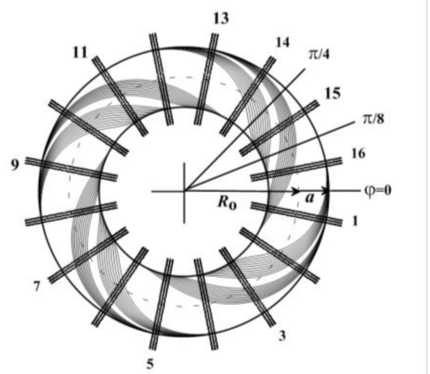

Fig. 1. Top view of the magnetic system of the U-2M torsatron magnetic system calculation model

In the present calculations the transverse compensating magnetic field B_z directed along the straight axis z of the torus is considered as an uniform one. Besides the value of this compensating field, also the ratio B_0/b_0 (parameter $K_\varphi=1/(1+B_0/b_0)$) affects the magnetic surface configuration in the torsatron with additional toroidal magnetic field coils. Here B_0 is the additional toroidal magnetic field generated by the coils on the geometric circular axis of the torus, b_0 is the amplitude of the toroidal component of the magnetic field generated by the helical currents on the same axis.

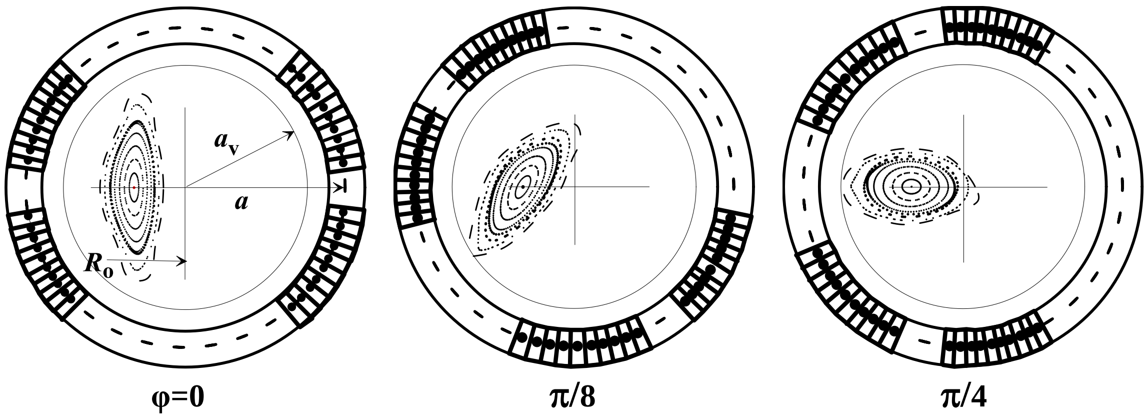

Fig. 2. Poloidal cross-sections of the magnetic surface configuration in the initial calculation model of the U-2M torsatron magnetic system in the regime with planar magnetic axis, K_φ=0.43

Fig. 2 shows the poloidal cross-sections of the magnetic surfaces obtained using the initial calculation model. The cross-sections are spaced over the toroidal angle φ within the magnetic field half-period φ=0, π/8, π/4 (see Fig. 1). In the figures the dashed circles (radius *a*=0.2618) is the torus poloidal cross-sections with traces (bold black dots) of the helical coil conductors. The trace positions are obtained from the calculations. The inner circle (radius a_v=0.2) shows the cross-section of the vacuum chamber of the U-2M torsatron device. It is seen from the figure that for the initial magnetic surface configuration we have chosen the configuration in the regime with the last closed magnetic surface not crossing the vacuum chamber wall and the planar magnetic axis. The magnetic axis of the configuration has the shape of the circle (radius R_{ax}=0.916) lying in the torus equatorial plane. The regime was realized with corresponding compensating magnetic field value B_z/b_0=0.507 and additional toroidal magnetic field value B_0/b_0=1.32 ($K_φ$=0.43). Fig. 2 also represents the cross-sections of closely spaced magnetic surfaces between which the rational resonance magnetic surface ι=0.5 takes place (ι is the value of field line rotational transform angle in 2π units).

The inner dashed lines in the Fig. 2 show the calculated cross-sections of the surface of the outer boundary of the stochastic field line layer [13, 14], i.e. the boundary of the plasma layer having transient plasma parameters (SOL plasma). It is seen that in the magnetic system under consideration in certain cross-sections the stochastic field line layer can traverse the contour of the vacuum chamber wall.

2. PERTURBED CONFIGURATION

The magnetic island structure excitation near the edge of the initial configuration of closed magnetic surfaces in the calculation model of the U-2M torsatron magnetic system was investigated using the shunting of the additional toroidal magnetic field coil 14 (see Fig. 1). The scheme of shunting is represented in Fig. 3. Here N_c=16 is the number of the additional toroidal magnetic field coils, r_c is the electrical resistance of a single coil, r_{sh} is the resistance of the shunt, U_G is the effective voltage on the direct-current generator. The shunt resistance is $r_{sh}=(1-k)r_c/k$, where $k=1-I_c/I$ and I_c/I is the ratio of the current I_c in the shunt coil to the total current *I* in the electric circuit.

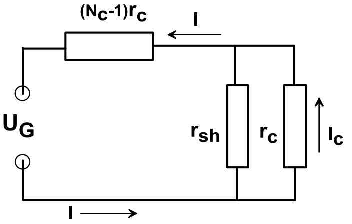

Fig. 3. The scheme of shunting one of the toroidal magnetic field coils

For the initial configuration *k*=0, so the shunt resistance $r_{sh}\to\infty$, i.e., the shunting is absent at all. For $k\to1$ the shunt resistance $r_{sh}\to0$, that is an equivalent of the shunt coil total de-energizing ($r_c\neq0$, nonsuperconducting coil). The case of such strong shunting was described previously in a regime with decreased value of $K_φ$ parameter [12]. If *k*=0.09 (reasonable shunting) then in the electrical circuit with electro-technical parameters of the U-2M torsatron magnetic system, where $r_c=2.4\times10^{-3}\Omega$, the shunt resistance value is to be $r_{sh}=24.3\times10^{-3}\Omega$.

2.1. PERTURBED MAGNETIC SURFACE CONFIGURATION (*k*=0.09)

The calculated poloidal cross-sections of magnetic surfaces obtained with a reasonable shunting of the coil 14 (see Fig. 1) are shown in Fig. 4. The evident difference of the perturbed magnetic surface configuration from the initial one is a magnetic island appearance nearby the magnetic surface configuration edge. The island is on the initial rational magnetic surface ι=0.5 site. So the magnetic axis of the island closes on itself after *m*=1 go-round in the poloidal direction resulting in the *n*=2 go-rounds in the toroidal direction. Outside the island there are no regular closed magnetic surfaces. The ranging calculations show that a noticeable layer of undestroyed magnetic surfaces outside the island appear with a light shunting (*k*=0.02) at the expense of two-fold decrease in the island maximal width in the torus poloidal cross-section φ=0. Two fold decrease in the resistance r_{sh} value (rough shunting, *k*>0.18) leads to a rough destruction of the island itself. Within the accuracy of calculations performed (~$10^{-3}R_0$) the magnetic axis geometry is not appreciably changed and the cross-sections of the surface of outer boundary of the stochastic field line layer remains invariable.

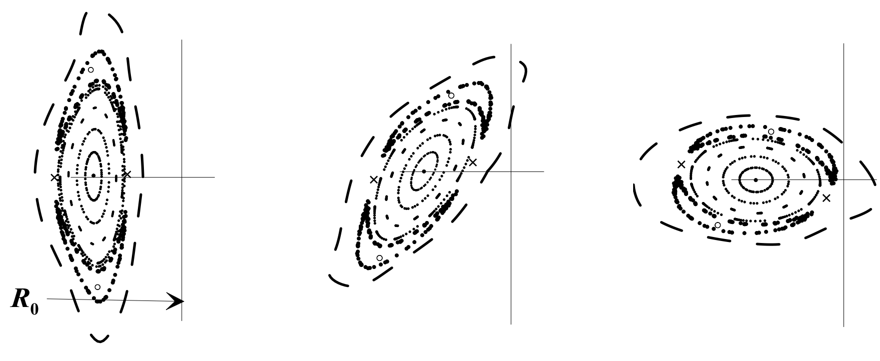

Fig. 4. The magnetic surface poloidal cross-sections obtained with reasonable shunting (k=0.09) of the coil 14, o *is an island magnetic axis position (O-point),* x *is a separatrix rib position (X-point)*

2.2. MAGNETIC FIELD PERTURBATION CHARACTERISTICS

Fig. 5 gives an idea of reasonable shunting (k=0.09) influence on the torsatron magnetic field. The starting points of the calculations of the initial and perturbed magnetic field line were the same.

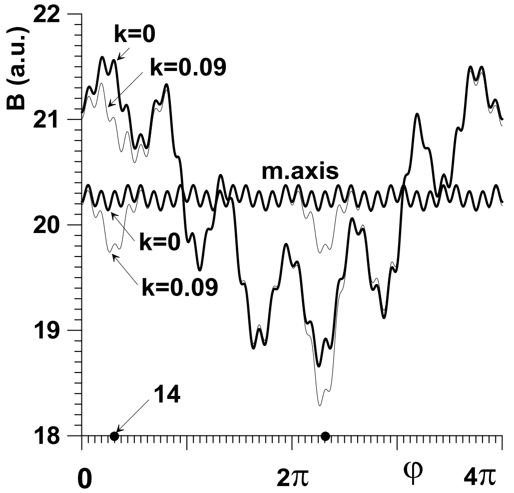

Fig. 5. Distribution of the magnetic field module B value along the magnetic field line in the initial (k=0) and perturbed (k=0.09) configurations on the magnetic surface and on the magnetic axis (m. axis). The toroidal azimuth of the shunt coil 14 is indicated

It is seen from the figure that the distribution of the module B value along the magnetic field lines represents a spatial oscillating process comprising the short, intermediate and long wavelength. The presence of the short (small-scale) mode with the azimuth period $\Delta\varphi=\pi/8$ is explained by the discreteness of the system of the additional toroidal magnetic field coils (N_c=16). The source of the intermediate azimuth period is the spatial value of the helical coil magnetic field period $2\pi/lm_h$. The presence of the largest azimuth period $\Delta\varphi\sim4\pi$ is due to the rotational transform angle value on an under study magnetic surface, $\Delta\varphi\sim2\pi/\iota$. A magnetic surface toroidicity determines the long wavelength amplitude of the module B oscillations.

One can see from the figure that perturbation contributed by the shunt coil 14 to the initial magnetic field is localized in the neighborhood of the coil 14 within one helical magnetic field period. Near the magnetic axis where the oscillation amplitudes are rather small and superposition principle is satisfied the value of perturbation can be estimated as module B difference between the initial and perturbed configurations at the coil 14 azimuth. Under the estimations the relative value of the magnetic field perturbation on the magnetic axis is $\delta B/B_{ax}\approx0.025$, B_{ax} is the module B value on the magnetic axis at the coil 14 toroidal azimuth in the initial configuration. Over the range k=0.02 to k=0.18 the perturbation relative value $\delta B/B_{ax}$ increases from 0.005 up to 0.05. It does not contradict the results of testing analytical and numerical calculations for the current-carrying circular turn plunged into an axisymmetric toroidal magnetic field.

2.3. INFLUENCE ON THE MAGNETIC SURFACE PARAMETERS

The magnetic surface parameters as functions of the magnetic surface average radius for initial and perturbed configurations are presented in Fig. 6. It can be seen from the figure that the average radius of the last closed magnetic surface is r_{lc}=0.074 in the initial configuration. The rotational transform angle increases with radius within $\iota_{ax}\rightarrow\iota_{lc}=0.35\rightarrow0.6$. The resonant value ι=0.5, being sensitive to the magnetic field perturbation is at r_r=0.058. There is slight magnetic hill, U=0.012. The mirror ratio range is within $\gamma_{ax}\rightarrow\gamma_{lc}=1.01\rightarrow1.23$, $\gamma=B_{max}/B_{min}$, where B_{max} and B_{min} denote the maximum and minimum magnetic field value on the magnetic surfaces.

The magnetic island excitation in the perturbed configuration (k=0.09) is accompanied by the last closed magnetic surface average radius decrease down to r_{plc}=0.053. The ranging calculations show that over the range k=0.02 to k=0.18 the average radius of the last closed magnetic surface decreases from r_{plc}=0.056 down to r_{plc}=0.05 in the perturbed configuration. It follows from the Fig. 6 that the magnetic surface parameters in the perturbed configuration differ a little from the initial configuration magnetic surface parameters in the r<0.53 range.

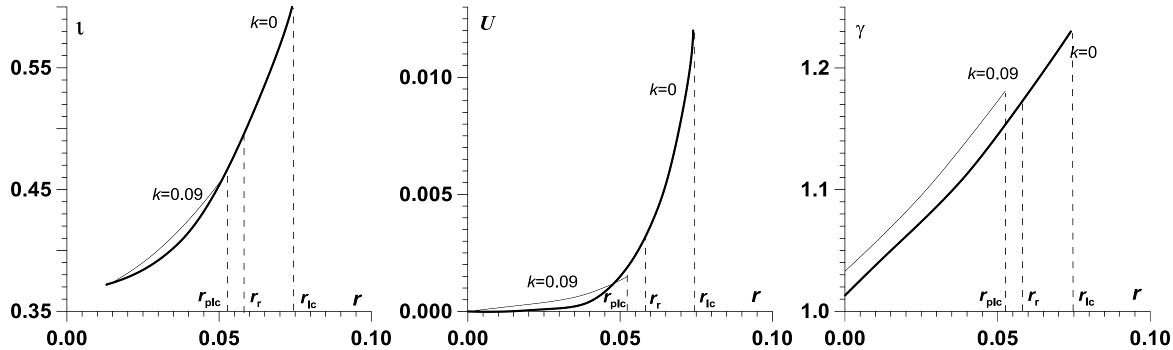

Fig. 6. Rotational transform angle (ι in 2π units), magnetic hill U, mirror ratio γ versus the value of the magnetic surface average radius r in the calculation model of the magnetic system for initial (k=0) and perturbed (k=0.09) configurations. The radii of the resonant (r_r) and the last closed magnetic surfaces (r_{lc} , r_{plc}) are pointed out

CONCLUSIONS

In the paper via numerical calculations the possibility of an accessible realization of the magnetic island structure excitation near the edge of closed magnetic surface configuration in the magnetic system comprising a discrete set of toroidal magnetic field coils is shown. The island structure arises due to the influence of the magnetic field perturbation, produced by particular shunting of electrical current in one of the coils.

As an example, the influence of a shunting on the magnetic surface configuration in the torsatron U-2M functional magnetic system in the regime with the last closed magnetic surface not crossing the vacuum chamber wall and the planar magnetic axis was investigated. It follows from the calculations that a decrease (k~0.01…0.2) of electric current in one of the torsatron U-2M magnetic system additional toroidal magnetic field coils results in a controllable magnetic island appearance near the magnetic surface configuration edge at the initial rational magnetic surface ι=0.5 site.

ACKNOWLEDGEMENTS

The authors are grateful to Dr. V. S. Voitsenja for problem definition and support.

REFERENCES

1. T.E. Evans et al. Suppression of large edge localized modes with edge resonant magnetic fields in high-confinement DIII-D plasmas *// Nucl. Fusion.* 2005, v. 45, p. 595.
2. T.E. Evans et al. RMP ELM suppression in DIII-D plasmas with ITER similar shapes and collisionalities // *Nucl. Fusion.* 2008, v. 48, p. 024002.
3. W. Suttrop et al. Studies of edge localized mode mitigation with active in-vessel saddle coils in ASDEX Upgrade // *Plasma Phys. Control. Fusion.* 2011, v. 53, p. 124014.
4. M. Becoulet et al. Mechanism of ELM mitigation by RMPs // *Phys. Rev. Lett.* 2014, v. 113, p. 11500.
5. K. Ichiguchi et al. Three-dimensional MHD analysis of Heliotron plasma with RMP // *Nucl. Fusion.* 2015, v. 55, p. 073023.
6. Y. Narushima et al. Experimental observation of response to resonant magnetic perturbation and its hysteresis in LHD // *Nucl. Fusion.* 2015, v. 55, p. 073004.
7. O. Motojima, A.A. Shishkin. Drift island motion in helical plasma and its use for ash removal and high-energy ion injection // *Plasma Physics and Controlled Fusion.* 1999, v. 41, p. 227.
8. R.I. Tanna. Novel approaches for mitigating runaway electrons and plasma disruptions in tokomak ADITYA *// FEC 24(2014).* Poster Session P7 EX/5-3.
9. D. Pfefferé et al. Impact of RMP magnetic field simulation models on fast ion losses // *Nucl. Fusion.* 2015, v. 55, p. 012001.
10. V.V. Nemov, S.V. Kasilov, W. Kernbichler, and V.N. Kalyuzhnyj. Study of collisionless high-energy charged particle losses for stellarators in presence of resonant perturbations of the magnetic field // *Journal of Plasma Physics.* 2016, v. 82, p. 515820101.
11. O.S. Pavlichenko. Status of “URAGAN-3M” and “URAGAN-2M” Experiments // *A Collection of Papers Presented at the IAEA* // *Technical Committee Meeting on Stellarators and Other Helical Confinement Systems.* Garching, Germany 10-14 May 1993, IAEA, Vienna, Austria.
12. V.G. Kotenko, V.E. Moiseenko, Yu.F. Sergeev, E.L. Sorokovoy, O. Ågren. Magnetic Surfaces of a Combined Magnetic System // *Problems of Atomic Science and Technology. Series “Plasma Physics“.* 2012, № 6(18), p. 22-24.
13. V.E. Bykov, Yu.K. Kuznetsov, A.V. Khodyachikh, O.S. Pavlichenko, V.G. Peletminskaya. Magnetic divertor in the l=3 torsatron //*A Collection of Papers Presented at the IAEA Technical Committee Meeting on Stellarators and other Helical Confinement Systems.* Garching, Germany, 10-14 May 1993, IAEA,Vienna, Austria, p. 391-396.
14. V.G. Kotenko. Possible Mechanism for Onset of Vertical Asymmetry of Diverted Plasma Fluxes in the Torsatron // *Fiz. Plazma.* 2007, v. 33, № 3, p. 280 (in Russian*), Plasma Phys. Rep.* 2007, v. 33, № 3, p. 249 (Engl.Transl.).
15. A.I. Morozov, L.S. Solovjev // *Voprosy teorii plazmy*. 1963, v. 2, p. 3-91 (in Russian).

Article received 15.10.2016

ВОЗБУЖДЕНИЕ ОСТРОВНОЙ СТРУКТУРЫ НА КРАЮ КОНФИГУРАЦИИ МАГНИТНЫХ ПОВЕРХНОСТЕЙ В ТОРСАТРОНЕ У-2М

В.Г. Котенко, В.Е. Моисеенко

С помощью численных расчётов показана возможность возбуждения островной структуры на краю конфигурации магнитных поверхностей в торсатроне с катушками дополнительного тороидального магнитного поля. Практическая схема реализации структуры основана на частичном шунтировании электрического тока в одной из этих катушек. Расчёты проведены с учётом геометрии действующей магнитной системы торсатрона У-2М.

ЗБУДЖЕННЯ ОСТРІВНОЇ СТРУКТУРИ НА КРАЮ КОНФІГУРАЦІЇ МАГНІТНИХ ПОВЕРХОНЬ У ТОРСАТРОНІ У-2М

В.Г. Котенко, В.Є. Моісеєнко

За допомогою чисельних розрахунків показана можливість збудження острівної структури на краю конфігурації магнітних поверхонь у торсатроні з котушками додаткового тороїдального магнітного поля. Практична схема реалізації структури заснована на частковому шунтуванні електричного струму в одній із цих котушок. Розрахунки проведені з врахуванням геометрії діючої магнітної системи торсатрона У-2М.