THE DIVERTOR REGION FORMATION IN THE STELLARATOR SYSTEM "YAMATOR"

G.G. Lesnyakov

Institute of Plasma Physics of the NSC KIPT, Kharkov, Ukraine
E-mail: lesn@kipt.kharkov.ua

By imposing a certain optimum vertical magnetic field and using the equi-inclination law of helical conductors winding, regularizations have been carried out for the region of the edge closed magnetic surfaces and the divertor region in the configurations of the l = 1, m = 3 and m = 5 Yamators. Magnetic configuration modes have been found, at which the narrowest regions with stochastic behavior of magnetic field lines are formed close to the conditional separatrices.

PACS: 52.55.-s; 52.55.Hc; 52.55.Rk; 52.70.Ds; 52.55.Dy

INTRODUCTION

The present work is a continuation of our earlier investigation on the l = 1 Yamator having a low aspect ratio $A_{h1} = R_0/a_{h1} = 3.333$ (R_0 being the major radius of the torus, $a_{h1}/R_0 = 0.3$ – the minor radius of the internal helical conductor), and a helical magnetic axis [1-4]. $A_{h2} = R_0/a_{h2} = 2.222$ ($a_{h2}/R_0 = 0.45$ – the minor radius of the outside helical conductor), $a_{h2} = a_{h1} + h$, $h/R_0 = 0.15$ - being the line conductor spacing. Apart from the rotational transformation angle, $i(a) \le 0.6$, (i is given in units of 2π, a is the radius of the last closed surface) and a significant magnetic well, ($-U$) > 8 %, the l = 1 Yamator is noteworthy for its unique feature, namely, two fins on the separatrices (two X-points).

Two X-divertors are formed at intersections of two characteristic separatrices of the l = 1 Yamator, Fig. 1. The separatrix fins of the l = 1 Yamator lie on both sides of the two-wire helical winding, being symmetrical relative to its azimuth. It is known that in most magnetic systems, the magnetic field toroidicity disturbs the separatrices. Consequently, their locations are called the conditional separatrices. The regions being in the neighborhood of the separatrices turn into the layers of magnetic field lines with stochastic behavior.

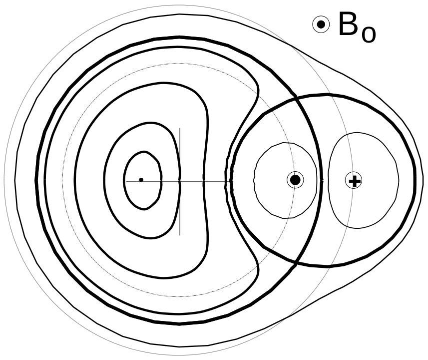


Fig. 1. Magnetic surfaces of the linear l = 1 Yamator. Solenoids of the longitudinal magnetic field are not shown. Two intersecting circles represent the separatrices. One of them (the greater) is the separatrix with a cylindrical magnetic surface, the part of which lies between the helical conductors. The rotational transformation on the separatrices is equal to i = m×l, where m is the number of magnetic field periods

The purpose of the research has been to analyze numerically the possibilities, which may appear helpful in regularizing the edge region of the plasma confinement volume, and/or the layer of magnetic field lines adjacent from the outside to the stochastic layer of the separatrix region. The outside layer of magnetic surfaces in the neighborhood of the separatrices was regularized in the l = 1, m = 3 and m = 5 Yamators either by matching the corresponding vertical field, or by applying the equi-inclination law of helical conductors winding instead of the common cylindrical law.

RESEARCH RESULTS

The main changes on regularization of both the structure of closed magnetic surfaces and the behavior of the field lines in the edge region are shown in Figs. 2 to 6. The edge region also includes the closed magnetic surfaces, which embrace the region of conditional separatrices.

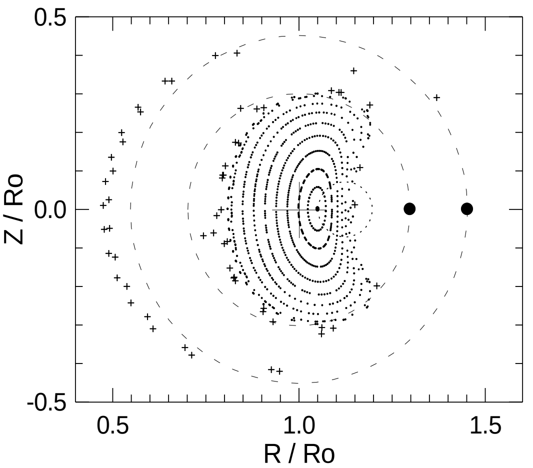


Fig. 2. Closed magnetic surfaces and magnetic field lines of the separatrix region, in the l = 1, m = 3 Yamator with helical conductors wound in accordance with the cylindrical law, $\theta = m\varphi$ (θ and φ are the poloidal and toroidal angles, respectively), without imposition of the external vertical magnetic field, $\boldsymbol{B_z}^{ext} = \boldsymbol{0}$. The poloidal cross-section of the torus is $\varphi = 0°$. The magnetic field of the stellarator toroidal solenoids, B_0, is described by the ratio $B_0/b_0 = 2.0$, where b_0 is the toroidal magnetic field of the helical conductor with the minor radius a_{h1}

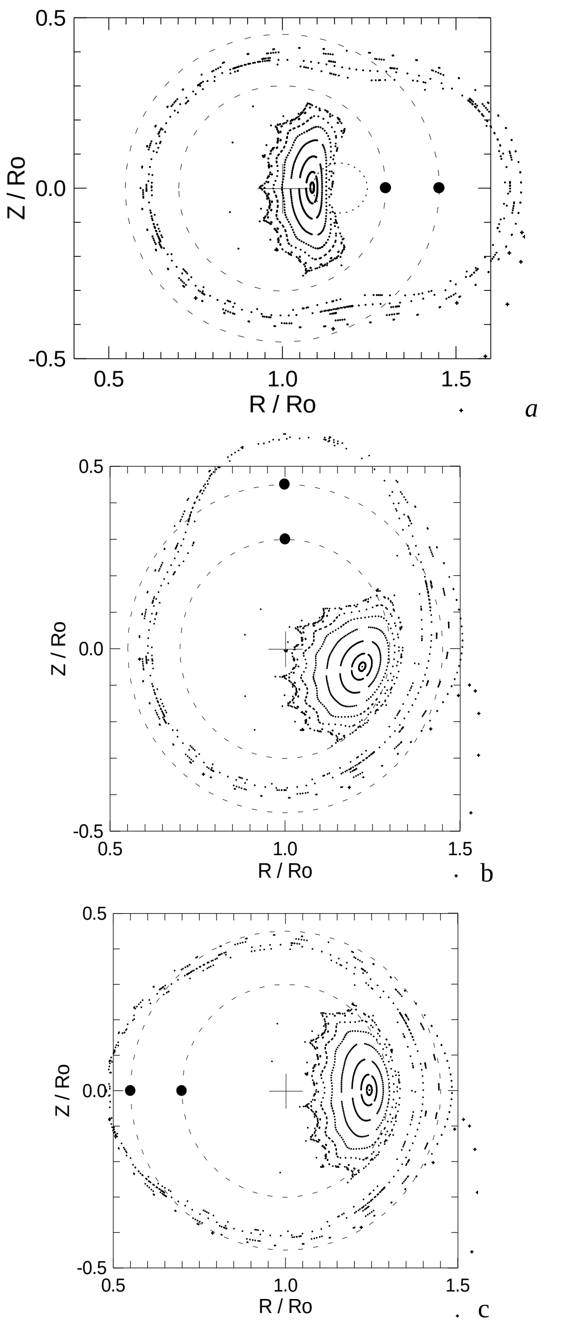


Fig. 3. Closed magnetic surfaces of the confinement volume and closed magnetic surfaces embracing the separatrix region of the l = 1, m = 3 Yamator with the cylindrical law of helical conductor winding, $\theta = m\varphi$, and the imposed vertical magnetic field $\boldsymbol{B_z^{ext}/B_0 = 0.014167}$ *($B_0/b_0 = 2.0$): a – poloidal cross-section of the torus $\varphi = 0°$; b – $\varphi = 30°$; c – $\varphi = 60°$ (magnetic field half-period)*

The crescent-shaped region (see Fig. 2), representing the remains of the separatrices and their neighborhood, is transformed into the layer of closed magnetic surfaces by imposing a certain optimum external vertical uniform magnetic field $\boldsymbol{B_z^{ext}}$ on the configurations under study for both $m = 3$ (see Fig. 3) and $m = 5$ (see Fig. 5) cases. The resulting layer encompasses the regions of two conditional separatrices. It should be noted that in the configuration with the imposed optimum vertical magnetic field, the magnetic axis is shifted towards the increasing major radius of the torus, while the mean radius of the closed magnetic surfaces is appreciably reduced. In the closed magnetic surface layer of the $l = 1$, $m = 3$ configuration, which embraces the conditional separatrices, the rotational transformation angle varies from $i_{+S} \approx 0.356$ (the surface with i_{+S} lies closer to the conditional separatrix) to $i_{end} \approx 0.1154$, and for the $l = 1$, $m = 5$ configuration it ranges from $i_{+S} \approx 0.604$ to $i_{end} \approx 0.48$.

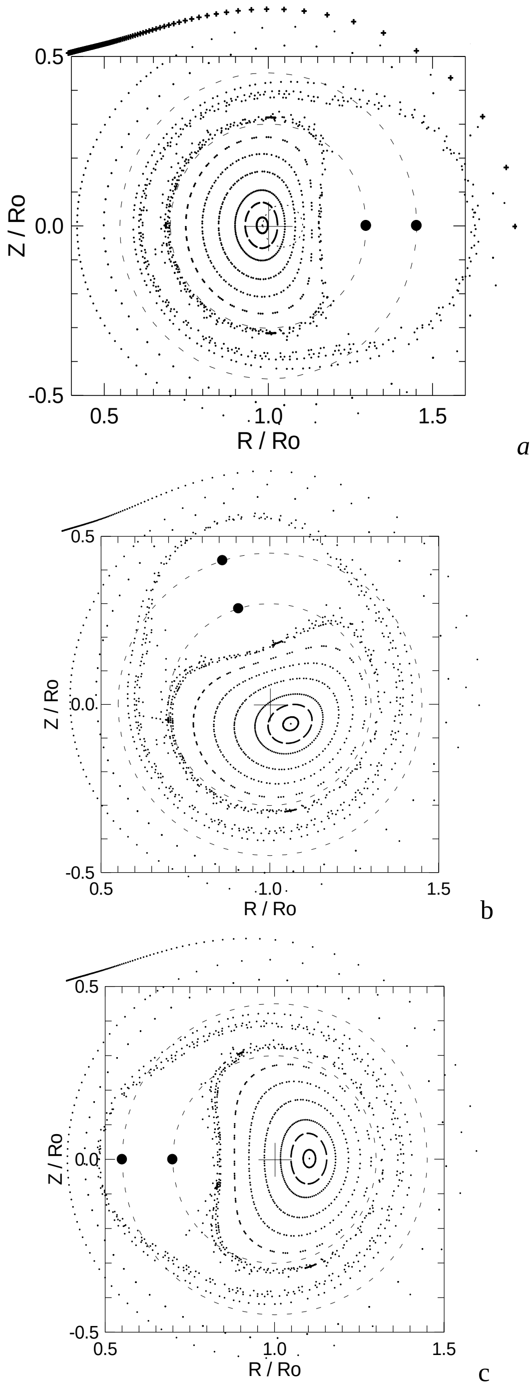
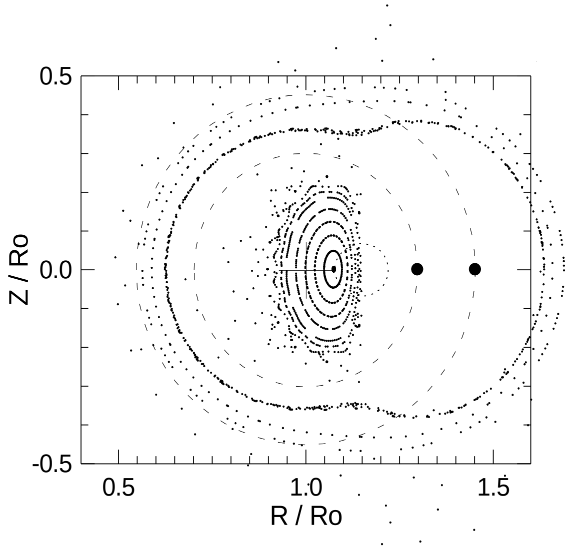
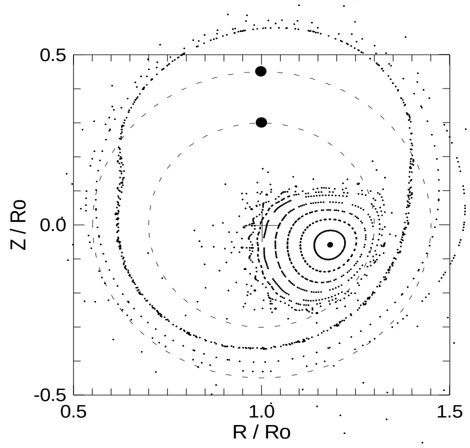


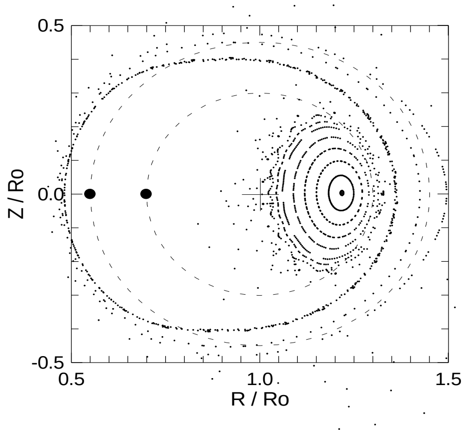
Fig. 4. Closed magnetic surface structure of the l = 1, m = 3 Yamator with the equi-inclination law of helical conductor winding, without imposition of the vertical magnetic field, $\boldsymbol{B_z^{ext} = 0}$ *($B_0/b_0 = 2.0$): a – poloidal cross-section of the torus $\varphi = 0°$; b – $\varphi = 30°$; c – $\varphi = 60°$ (magnetic field half-period). The region of conditional separatrices is well seen in the figures*



a



b



c

Fig. 5. Magnetic surfaces of the confinement volume and closed magnetic surfaces near the separatrix region of the l = 1, m = 5 Yamator with the cylindrical law of helical conductors winding, $\theta = m\varphi$, and the imposed vertical magnetic field $\boldsymbol{B_z^{ext}/B_0 = 0.0146}$ ($B_0/b_0 = 1.0$): a – poloidal cross-section of the torus $\varphi = 0°$; b – $\varphi = 30°$; c – $\varphi = 60°$ (magnetic field half-period)

The equi-inclination law of helical conductors winding, as applied to the configurations, leads to the recovery of the layer of closed magnetic surfaces outside the conditional separatrices, and makes it more stable even at $\boldsymbol{B_z^{ext} = 0}$ (see Figs. 4 and 6). For plasma confinement, it is particularly important that with the use of the equi-inclination law of helical conductors winding the maximum size of closed magnetic surfaces is created in the configuration. The magnetic axis lies closer to the geometrical axis of the torus, and the shear of magnetic field lines increases. The displacement of the external layer of closed magnetic surfaces to the separatrix location, and the increase of its transverse size can be also characterized by the value of rotational transformation angle on the magnetic surface nearest to the conditional separatrices, $i_{+S} \geq 0.6$.

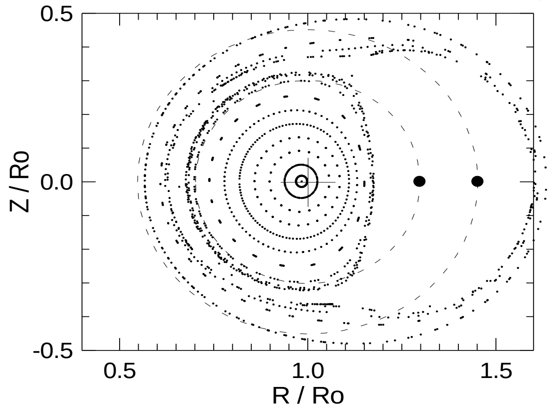


Fig. 6. Magnetic surface structure of the l = 1, m = 5 Yamator configuration with the equi-inclination law of helical conductor winding, without imposition of the vertical magnetic field, $\boldsymbol{B_z^{ext} = 0}$, $B_0/b_0 = 1.2$. Poloidal cross-section of the torus at $\varphi = 0°$

CONCLUSIONS

The present studies have demonstrated that the best regularization of the peripheral (edge) region and the divertor region of Yamators is attained in cases when for creating the magnetic configuration the equi-inclination law of helical conductors winding is applied. The modes of magnetic configurations for $l = 1$, $m = 3$ and $m = 5$ Yamators have been found, at which the narrowest region with stochastic behavior of magnetic field lines is formed in the neighbourhood of the conditional separatrices (see Figs. 4 and 6). The result is that this region with stochastic behaviour of magnetic field lines in the vicinity of the conditional separatrices of the Yamator appears to be embraced from the outside by closed magnetic surfaces. Moreover, these magnetic surfaces also form a closed spatial divertor region of quite great sizes in both longitudinal (azimuthal) and transverse directions. This is particularly significant for distribution and utilization of the heat of plasma that is diverted from the magnetic trap. One may reason much upon new functions and the mode of operation of the proposed divertor. But it is possible that the divertor structure of this sort and its updated development would meet the idea [5] that the advanced divertor solutions will set the innovative magnetic geometries.

REFERENCES

1. V.G. Kotenko, G.G. Lesnyakov, S.S. Romanov. Stellarator fields with 2-wire lines wound round the torus // *Problems of Atomic Science and Technology. Series "Plasma Physics"*. 1999, issues 1(1), 2(2), p. 49-51.
2. V.G. Kotenko, G.G. Lesnyakov, S.S. Romanov. Yamator: high magnetic-well value stellarator // *J. Plasma Fusion Res.* SERIES, 2000, Issue 3, p. 154-157.
3. G.G. Lesnyakov, V.G. Kotenko, E.D. Volkov. Mapping of magnetic field lines at the edge of the *l*=1 helical-axis Yamator // *International Conf. and School on Plasma Physics and Controlled Fusion.* September 16-21, 2002, Alushta (Crimea), Ukraine. Book of Abstracts, organiz. NSC KPTI, Kharkiv, Ukraine. 2002, p. 56.
4. G.G. Lesnyakov, V.G. Kotenko, E.D. Volkov. Mapping of magnetic field lines at the edge of the *l*=1 helical-axis Yamator // *Problems of Atomic Science and Technology. Series "Plasma Physics"* 2002, № 4 *(7)*, p. 67-69.
5. M. Kotschenreuther, S. Mahajan, P.M. Valanju, et al. Taming the heat flux problem: advanced divertors towards fusion power // *J. Fusion Energy*. 2016, v. 35, p. 27-30.

Article received 25.11.2016

ФОРМИРОВАНИЕ ОБЛАСТИ ДИВЕРТОРА В СТЕЛЛАРАТОРНОЙ СИСТЕМЕ ЯМАТОРА

Г.Г. Лесняков

С помощью наложения определённого оптимального вертикального магнитного поля и применения равнонаклонного закона намотки винтовых проводников осуществлены регуляризации областей краевых замкнутых магнитных поверхностей и дивертора в конфигурациях $l = 1$, $m = 3$ и $m = 5$ Яматоров. Найдены режимы магнитных конфигураций, в которых, вблизи условных сепаратрис, сформированы наиболее узкие области со стохастическим поведением силовых линий поля.

ФОРМУВАННЯ ОБЛАСТІ ДИВЕРТОРА В СТЕЛАРАТОРНІЙ СИСТЕМІ ЯМАТОРА

Г.Г. Лесняков

За допомогою накладання визначеного оптимального вертикального магнітного поля і застосування рівнонахиленного закону намотки гвинтових провідників виконані регулярізації областей крайових замкнених магнітних поверхонь та дивертора в конфігураціях $l = 1$, $m = 3$ и $m = 5$ Яматорів. Знайдені режими магнітних конфігурацій, в яких, поблизу умовных сепаратрис, сформовані найбільш вузьки області зі стохастичною поведінкою силових ліній поля.