# MAPPING OF MAGNETIC FIELD LINES AT THE EDGE OF THE *L*=1 HELICAL-AXIS YAMATOR

*G. G. Lesnyakov, V. G. Kotenko, E. D. Volkov*
*Institute of Plasma Physics, National Science Center*
*"Kharkov Institute of Physics and Technology", Kharkov 61108, Ukraine*

PACS: 52.55.-s

## 1. INTRODUCTION

Compared to magnetic traps of the same group, the $l$=1 Yamator magnetic field coils are the simplest in structure. In principle, the $l$=1 Yamator should be put in a row with Heliac-type spatial-axis stellarators. By definition given in papers [1,2], the term "Heliac" means the magnetic configuration, where the vertically elongated magnetic-surface cross-section shape rotates simultaneously with the principal normal with respect to the magnetic axis. The YAMATOR is a new magnetic system [3, 4], where two-wire lines wound round the torus are plunged into an axisymmetric toroidal magnetic field. The wires of the two-wire line with equal and opposite currents have the same pitch of winding $L$ and are placed on the nested tori of one and the same major radius $R_0$ and of different minor radii $a_1$ and $a_2 = a_1 + h$, $h$ being the line wire spacing. The number of two-wire lines determines Yamator's multipolarity $l$.

In the $l$=1, m=3 toroidal Yamator (m is the number of magnetic field periods) with a low aspect ratio $A_{h1}=R_0/a_1 \approx 3.333$ and $r_{ax}/a_1 \leq 0.4$ ($r_{ax}$ is the radius of the helical magnetic axis), a significant magnetic well, (-U)≥8%, and a rotational transform, $i \leq 0.6$ ($i$ is given in units of $2\pi$), greater than the one in other-multipolarity Yamators [3, 4] can be formed. At the same time, the $l$=1 Yamator has the unique peculiarity [4]: there are two separatrix ribs (two X-points are the intersection points of two separatrices) that lie on both sides of the two-wire helical winding (line), symmetrically about its the azimuth.

It is known that the magnetic field toroidicity leads to the destruction of the separatrix region, which is replaced by a stochastic layer. Therefore, it is interesting to know how it occurs in the low aspect ratio magnetic system.

The aims of this paper have been: (i) to investigate numerically the special features in the behavior of $l$=1 Yamator magnetic field lines, the trajectories of which start immediately after the last closed magnetic surface, (ii) to obtain footprints of magnetic field lines near the conventional separatrix and X – points, and (iii) to conceive even if in part the possibilities of this magnetic divertor.

## 2. SPECIAL FEATURES OF LOW ASPECT RATIO YAMATOR

Numerical calculations have been carried out for the filamentary-wire model and are the continuation of investigations of the $l$=1, $m$=3 Yamator [3]. The basic parameters of the configurations were as follows: $\Theta = m\varphi$ is the law of the two-wire helical winding, $\Theta$ is the poloidal angle, $\varphi$ is the toroidal angle; $h/R_0=0.15$; $A_{h1}=R_0/a_1=3.333$ and $A_{h2}= R_0/a_2=2.222$ are the aspect ratios of the nested tori. The $B_0/b_0$ ratio ($B_\varphi=B_0R_0/R$, $b_o$ is the helical current-generated field of radius $a_1$) determines the structure and properties of magnetic surfaces in the configuration. A controlling uniform transverse magnetic field $B_Z$ was not applied.

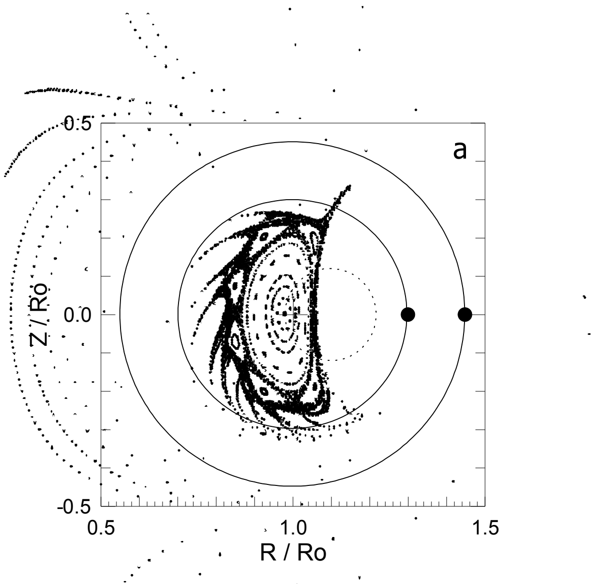
### 2.1. Behavior of magnetic field lines in the periphery region

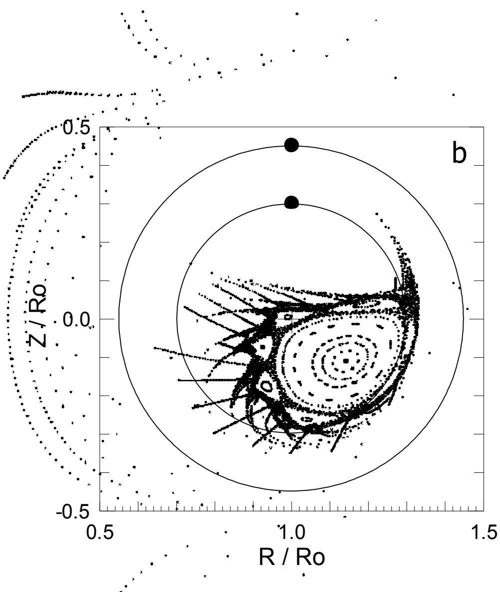
The structure of magnetic field lines in the $l$=1, $m$=3 Yamator in the region of closed magnetic surfaces (CMS) and in their periphery is shown in Fig.1. This structure exhibits the following special features. It the edge region of CMS there is a chain of large-size "natural" magnetic islands, $i$=3/6. Outside the CMS region a wide stochastic region lies. The stochastic region originates as a layer, where large-size island chains overlap and break down with simultaneous formation of the whisker field lines that extend up to the conventional separatrix. The whiskers are the hypertrophied remains resulting from the break of the large-size island chains, where the islands with $i$=5/10 predominate. The general pattern of the behavior of magnetic field lines that form the whiskers in the Yamator does not differ, in principle, from the field line pattern in the $l$=2 heliotron/torsatron [5]. To that description it should be added only that "folding" of the whiskers takes place towards the rotational transform and is stipulated by magnetic line shear. The conventional separatrix is assumed to be the toroidal surface of minor radius $r_s$=0.3674 that is the same as for the separatrix surface of a straight magnetic configuration. The magnetic system toroidicity destroys the separatrices and the CMS neighbouring with them, i. e. the ones that must embrace the separatrices as a whole, and thus the stochastic region is extended. As a result of this process, a crescent region is formed on the inside of the torus.

When obtaining the structure of the magnetic field lines in the stochastic region, 1086 field lines started along 24 radial directions equally spaced in the angle $\Theta$ in the $\varphi$=0° poloidal cross-section. The idea about the starting point positions can be gained from the points of the first intersection of the field lines with the cross-sections of the torus φ=30°, Fig.1b, and φ=60°, Fig.1c.

In order to gain more the idea about the magnetic divertor, all open field lines were traced up to their intersection with the toroidal surface of conventional separatrix $r_s$. The map of toroidal coordinates $\Theta$, $\varphi$ footprint intersection with the $r_s$ surface is shown in Fig.2. Of the total number of the starting field lines only 67% (731) of lines intersect the $r_s$ surface without being noticeably affected due to the hardness phenomenon at numerical integration of magnetic field line differential equations [6], this being the case in the Yamator. The footprints of these field lines lie to the left from the helical winding and present the divertor possibilities. The magnetic field line trajectories on the outside of the CMS region must be calculated with a substantially improved integration accuracy of differential equations (a small step of integration is also needed). In our calculations the fourth-order Runge-Kutta integration method of differential equations with a double accuracy was used (step of integration $\lambda$, $\lambda/2\pi R_o \leq 5\times10^{-4}$). Nevertheless, the fulfillment of these requirements does not eliminate the hardness phenomenon for differential equations [6]. As it is seen from Fig.2, the location of magnetic field line footprints in the first magnetic field period extends in rays along the φ coordinate, and in the other two magnetic field periods similar rays are transformed into the nested spiral loops.

In integration of magnetic field line equations 355 (33%) field lines out of 1086 field lines undergo jumps. In Fig.2, the footprints of the onset of jumps lie to the



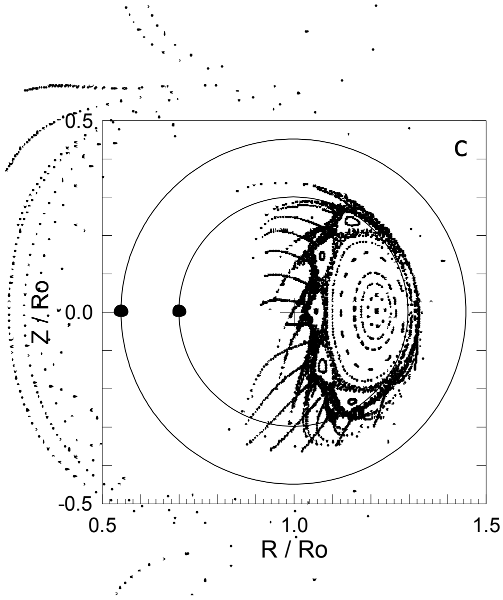




*Fig.1. Magnetic field line structure in the l=1, m=3 Yamator, $B_o/b_o=1.0$, $B_z/B_o=0$, $r_{cl}/R_o=0.16$, $i(0)=0.44$ u $i_{cl}=0.52$ (in units of 2π), (-U)=10% ($r_{cl}$ and $i_{cl}$ are the minor radius and the rotational transform of the last closed magnetic surface, corresponding): a) the φ=0° poloidal cross-section (the dashed circumference in the central part shows the excursion of the helical magnetic axis); b) φ=30° (one quarter of the field period); c) φ=60° (middle of the field period).*

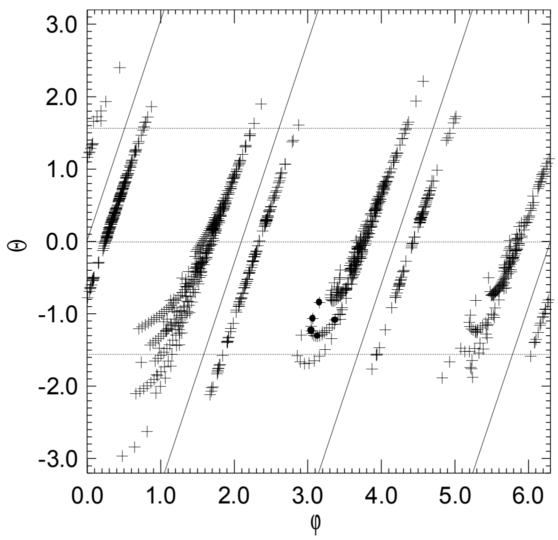



*Fig.2. Footprints of magnetic field lines on the toroidal surface with the minor radius of the conventional separatrix* $r_s=(a_1a_2)^{1/2}=0.3674$. *The solid lines show the position of helical winding*.

right and closer to the helical winding. The coordinates of the onset of field line jumps (footprints) indicate where the hardness phenomenon takes place. In Yamators, the hardness is caused by magnetic field inhomogeneities. It appears at sites, where there is a close neighbourhood of two regions with different magnetic fields, in which the derivatives, great and small in magnitude, occur during the integration process, this being especially in the direction, where the high-value fields quickly decrease.

## 2.2. Magnetic field line trajectories in the vicinity of the conventional separatrix

A general idea about the behavior of short magnetic field lines, the lengths of which are shorter than the length of one transit along the torus, can be gained from Fig.3. The chosen trajectories of short magnetic field lines for the starting points of four radial directions are

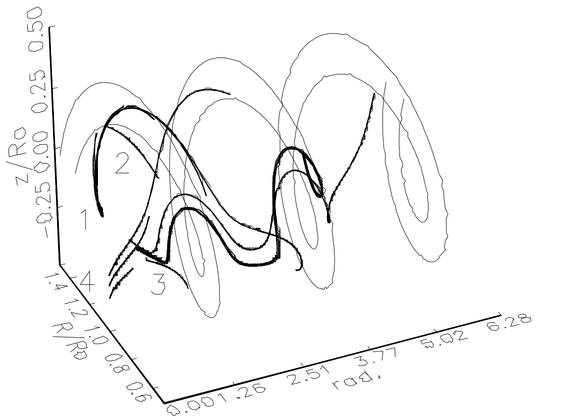



*Fig.3. Magnetic field lines that reach the conventional separatrix for less than one transit along the torus in the l=1, m=3 toroidal Yamator straightened along the φ coordinate (solid thin lines show the two-wire helical winding). The magnetic field line starting points lie along four radial directions: Θ=0˚ (lines 1); Θ=90˚ (2); Θ=180˚ (3); Θ=270˚ (4).*

typical, in principle, for the end segments of all field lines that approach both the X-points and the conventional separatrix $r_s$. In this series of magnetic field lines the thick line numbered as 3 is an example of the line, the trajectory of which goes round on the inside of the two-wire helical winding and ends with a jump because of the hardness phenomenon.

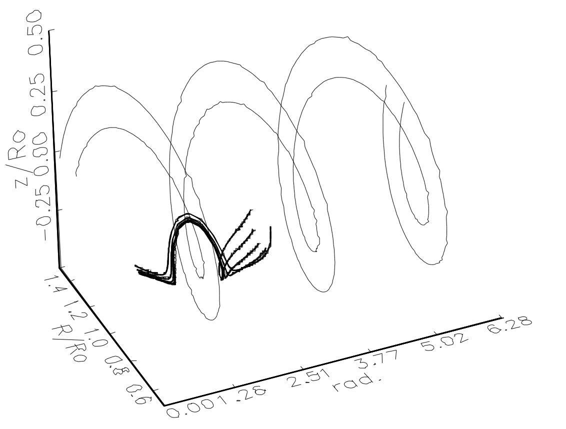



*Fig.4. Magnetic field line trajectories that belong to the spiral structure of the footprints indicated in* Fig.2 *by bold dots*.

The field line trajectories of five footprints (they were chosen along the spiral, bold dots in Fig.2) allow an understanding of the mechanism of spiral structure formation in the Yamator. The starting points of these trajectories are located only along the radial direction $\Theta$ =195° in the range $0.25853 \le r \le 0.30053$. The three-dimensional tracing of these lines in the straightened torus (Fig.4) shows the region being a peculiar kind of a field-line scattering generator as these field lines approach to the X-points. In this region, the hardness of the set of magnetic field line equations and, as a consequence, the field line jumps take place. Both these phenomena are due to the magnetic field gradient being opposite to the direction of field line motion (see above). The impact parameter of the scattering process is determined by the magnetic field line trajectory in the stochastic region, and, therefore, each spiral is spread due to a stochastic instability of motion.

## 3. SUMMARY

The present investigations give the general idea about the magnetic field line structure in the edge region of the *l*=1 Yamator with a low aspect ratio and a helical magnetic axis. The locations of the magnetic footprints on the surface of the conventional separatrix give evidence for both their broadening along the torus, and formation of nested spiral structures. The main mechanism of spiral structure formation of the footprints is the chaotic scattering of magnetic field lines on the magnetic field inhomogeneities, typical of Yamator, when the field lines approach the X-points and the conventional separatrix. The degree of scattering is stipulated by the degree of hardness of the set of magnetic field line equations. The spiral structure of the magnetic footprints in the Yamator resembles partly the spiral structure of the magnetic footprints in the two-wire model of the divertor field configuration with a separatrix (magnetic geometry is similar to the DIII-D tokamak) [7-9]. In the *l*=1 Yamator, as also in the *l*=2 Yamator [10], the magnetic field lines forming the divertor arrive for the most part at the surface of the conventional separatrix only on the outside half of the torus, that points to the possibility of creating a discrete divertor.

## REFERENCES

1. V. D. Shafranov. J. Plasma Fusion Res. SERIES, Vol. 1, 70-74 (1998).
2. M. Isaev et al. J. Plasma Fusion Res. SERIES, Vol. 1, 66-69 (1998).
3. V. G. Kotenko et al. *Problems of Atomic Science and Technology*. Series: Plasma Physics, Issues **1**(1), **2**(2), 49-51 (NSC "KIPT", Kharkov, 1999).
4. V. G. Kotenko et al. J. Plasma Fusion Res. SERIES, Vol. 3, 154-157 (2000).
5. H. Akao. J. Phys. Soc. of Japan, Vol. 59, No. 5, 1633-1646 (1990).
6. A. B. Arushanyan, S. F. Zaletkin. Numerical solution of ordinary differential equations using FORTRAN. M.: Moscow University, 1990 (in Russian).
7. S. S. Abdullaev, G. M. Zaslavsky. Phys. Plasmas **2** (12), 4533-4541 (1995).
8. N. Pomphrey, A. Reiman. Phys. Fluids B**4**, 938-948 (1992).
9. S. S. Abdullaev, G. M. Zaslavsky. Phys. Plasmas **3** (2), 516-528 (1996).
10. G. G. Lesnyakov et al. *Problems of Atomic Science and Technology*. Series: Plasma Physics (6), N 6, 68-70 (NSC "KIPT", Kharkov, 2000).