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Structure of the edge magnetic field of the l=2 Yamator

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1. Introduction

It is probable, that in future reactor-size toroidal-confinement devices a divertor would become indispensable, and this requirement would determine the choice of the magnetic system also. It is known [1] that a divertor is an integral part of helical stellarator-type magnetic systems. However, its properties depend on the magnetic field configuration (e. g., see, for example, ref. [2]) and thus govern the practical design of the divertor.

A new helical magnetic system called Yamator [3-5] also belongs to the class of stellarator-type systems. At moderate values of basic magnetic-surface characteristics and a large relative volume of closed magnetic surfaces (CMS), a significant magnetic well can be created in Yamators. The Yamator magnetic system is analogous to the one of a classical stellarator with the only difference that the poloidal magnetic field components are here formed with the help of 2-wire lines wound round the torus. The wires of each of 2-wire lines, wound with equal and opposite currents, have the same pitch of winding L and are placed on the nested tori of 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 2-wire lines determines the Yamator polarity *l*.

The aim of this paper is to elucidate special features of field lines behaviour in the magnetic field edge structure of the *l*=2 Yamator and to gain an idea about field-lines divertor functions.

2. Linear configuration of the *l*=2 Yamator

In accordance with [6], if a magnetic field has a helical symmetry and $(2\pi a_2/L)^2 \ll 1$, the magnetic surface function in the *l*=2 straight Yamator can be defined analytically as:

$$\Psi(r,\theta) = (\mu_0 I/4\pi)\Big\{\eta r^2/a_1^2 - \ln[1+(r/a_1)^4 - 2(r/a_1)^2\cos 2\Theta] + \ln[1+(r/a_2)^4 - 2(r/a_2)^2\cos 2\Theta]\Big\}$$

where I is the helical wire current, $\eta=2\pi\varepsilon a_1 B_0/\mu_0 I$, $\varepsilon=2\pi a_1/L$, B_0 is the longitudinal magnetic field and $\Theta=\theta-2\pi\zeta$ in terms of cylindrical coordinates r, θ, ζ. At coincident the signs of B_0 and b_0 (b_0 being the field on the geometrical axis of the system, caused by the helical current I at radius a_1), and in accordance with the η parameter there exist closed contours of magnetic-surface cross-sections that correspond to the solution of the Ψ=const equation, Fig.1.

Compared to a straight classical stellarator or a torsatron, the edge magnetic field structures in these new systems have a double number of separatrix ribs (so-called "X-points"). The X-points are the intersection points of two separatrices (thick curves in the figure), one of which is small and it embraces the 2-wire line. In the Yamator, at a given current I, its shape and size depend only on the longitudinal magnetic field value. The other, the larger separatrix is determined from the condition $\partial\Psi/\partial\Theta=0$ and it has the minor radius $r_s=(a_1a_2)^{1/2}$. The X-points lie symmetrically relative to the azimuth of this helical coil, and their angles are determined from the condition $\partial\Psi/\partial r\,|_{r_s}=0$,

$$\Theta = \pm\frac{1}{2}\arccos\left\{\frac{a_1^2+a_2^2}{2r_s^2}\left[1-\frac{a_2^2-a_1^2}{\eta r_s^2(a_1^2+a_2^2)}\right]\right\}.$$

For the magnetic surface structure shown in Fig.1, the angle positions of X-points, $\Theta\approx\pm23.9°$, are determined by the given expression exactly.

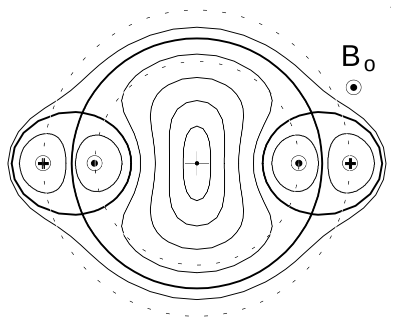


Fig.1 The magnetic surface structure in the l=2 straight Yamator with the dimensionless parameter η=1.35 *that determines the ratio of the longitudinal magnetic field* B_0 *to the helical current-generated field* b_0 *of the radius* a_1. *The coils of the longitudinal magnetic field are not shown*

3. Toroidal Yamator

In the previous paper [3], study was made into the structure and properties of the magnetic surfaces in the *l*=2, *m*=3 toroidal configurations of the Yamator system: the average minor radius of the last CMS was r_{lc}/R_0=0.23÷0.28, the rotational transform i_{lc}=0.25÷0.45 (in units of 2π), the magnetic well was (-*U*)=10÷25%.

The present paper is a continuation of those investigations of the *l*=2, *m*=3 Yamator with the emphasis on the study of the magnetic field edge structure. Numerical calculations have been carried out for the models with filamentary wires. The basic parameters of the configurations were as follows: a 2-wire line wound a round the torus along the helical line $\Theta=m\varphi$, Θ - poloidal angle, φ - toroidal angle, *m* - the number of helical pitches over the length of the torus; h/R_0=0.15; the aspect ratio of the nested tori

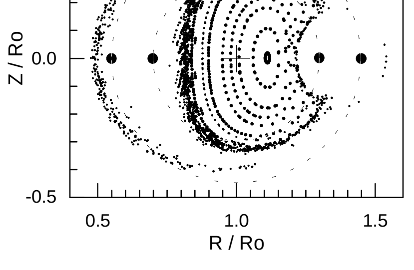
$A_{h1}=R_0/a_1=3.333$ ($a_1/R_0=0.3$) and $A_{h2}=R_0/a_2=2.222$ ($a_2/R_0=0.45$).

A set of 2-wire lines is plunged into the axisymmetric toroidal magnetic field $B\varphi=B_0R_0/R$, where R is the radial position of the observation point, reckoned from the straight axis of the system, z. The ratio B_0/b_0 determines the structure and properties of magnetic surfaces in the configuration. The superposition of a controlling uniform transverse magnetic field B_z is possible.

3.1. Characteristics of edge magnetic fields in the Yamator

Numerical tracing of magnetic field lines was used to obtain the magnetic field structure of different configurations in the l=2, m=3 low aspect ratio Yamator, Fig.2, was obtained. The variations of the edge field structure (beyond the last CMS) were caused by both the transverse magnetic field (Fig.2a,b) and the toroidal magnetic field (Fig.2c). In the toroidal geometry, there occur a shift to the outside and a disturbance of the magnetic surfaces that embrace all helical wires as a whole (see Fig.1) and the separatrices, too. As a result, crescent magnetic surfaces can be observed on the left side of the edge region (Fig.2a). It also turns out that with variations in the transverse magnetic field there exists its optimum value, B_z/B_0=-0.0166, at which it appears possible to hold a comparatively thin layer of the magnetic surfaces immediately around the conventional separatrix. In this case, the magnetic surface structure in the toroidal geometry, near the separatrix, become similar to the straight configuration, see Fig.1. It can be also seen, that at the left and at the right from the CMS the shape and size of the small separatrix are inversely proportional to the magnetic field value and they obey its radial dependence. Fig.2c shows the magnetic field structure in the configuration, when by decreasing the toroidal magnetic field one can attain i=0.41 the CMS region, still keeping a rather high magnetic well. The choice of equal inclination law of winding for the 2-wire helical lines in the configuration provides the largest volume of CMS ($r_{lc}\geq a_1$) with the magnetic axis near the geometrical axis of the torus and the region, around the conventional separatrix, gets symmetrized, Fig.2d. However, such a configuration looses the magnetic well.

The structure of mod-B contours, Fig.3, appears helpful to reveal the peculiarities of magnetic field



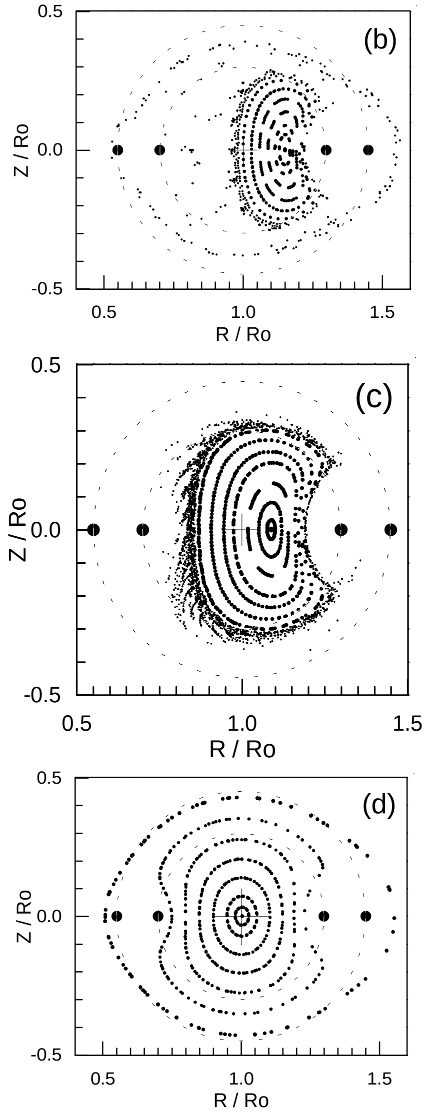


Fig.2 Magnetic field line structure in the φ=0 *poloidal cross-section for four different configurations*: *a)* B_0/b_0=2.5, B_z/B_0=0, r_{lc}/R_0=0.27, i_{lc}=0.26 *(in units of* 2π*), (-U)*=25%; *b)* B_0/b_0=2.5, B_z/B_0=-0.0166, r_{lc}/R_0=0.225, i_{lc}=0.34, *(-U)*=15%; *c)* B_0/b_0=1.833, B_z/B_0=0, r_{lc}/R_0=0.255, i_{lc}=0.41, *(-U)*=11%, no shear; *d) equi-inclined 2-wire helical winding,* B_0/b_0=2.5, B_z/B_0=0, r_{lc}/R_0=0.331, i_{lc}=0.55, *the magnetic hill is (+U)*=15%, *shear*

formation and magnetic field line behaviour in the l=2 Yamator configurations. In contrast to the classical stellarator [7], the B_{min} regions in the Yamator (closed contours of B/B_0=0.633,0.972 in the φ=0° cross-section (Fig.3a) and of B/B_0=0.66,1.067 at the half of the magnetic field period, in the φ=30° cross-section (Fig.3b)) are removed from the operating volume and are located on each side of the 2-wire helical winding, beyond the minor radius a_1. The large separatrix passes through these regions, and the X-points coincide with the B_{min} points. It can be stated that the ergodic magnetic field line intersects the local region B_{min} in the vicinity of the X-point.

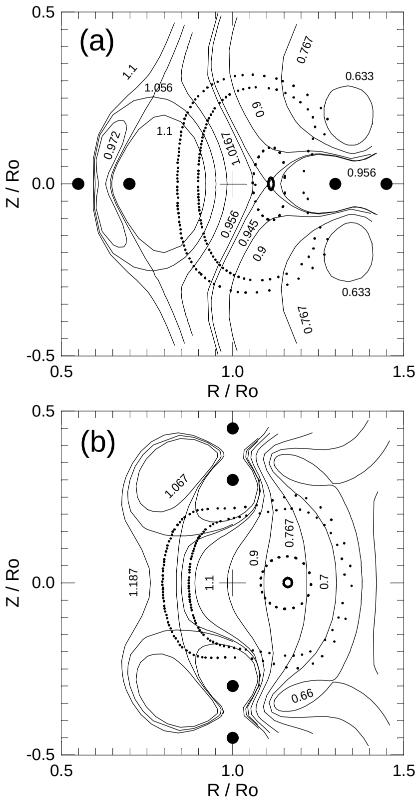


Fig.3. Constant B contours and different magnetic surfaces of the toroidal example (*l*=2, *m*=3 *Yamator, the configuration of Fig.2a): a)* φ=0 *cross-section*; b) φ =30° *cross-section*

The connection length of the ergodic lines reaching the conventional separatrix of radius r_s=0.367 falls off rather rapidly outside the CMS in the configurations understudy. The toroidal coordinates φ, Θ of the footprints of intersection of the escaping field lines with the toroidal surface of minor radius r_s are shown in Fig.4. The locations of these footprints are of vital importance for the choice of the divertor concept. Fig.5 furnishes insight into the behaviour of the edge magnetic field lines that intersect the r_s toroidal surface. Here, the magnetic field lines are shown in the three-dimensional presentation in the toroidal configuration straightened along the φ coordinate.

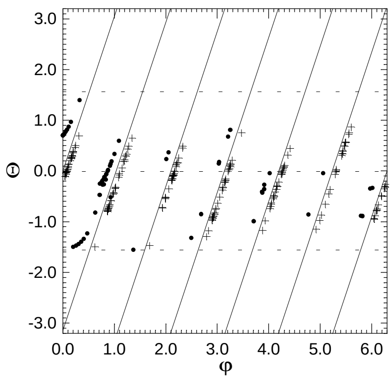


Fig.4. Footprints of edge field lines on the toroidal surface with the minor radius of the conventional separatrix $r_s=(a_1 a_2)^{1/2}$*. The solid lines show the positions of helical coils*

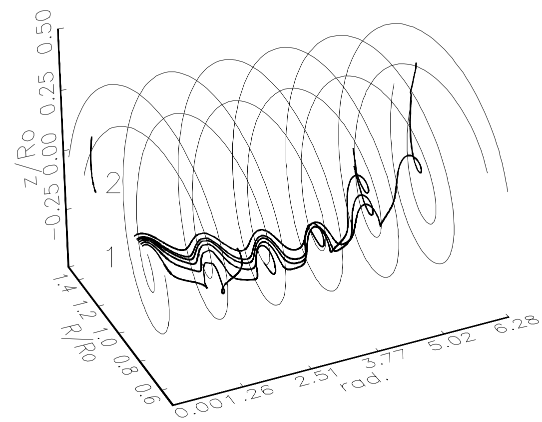


Fig.5. Magnetic field lines in the l=2, *m*=3 *toroidal Yamator straightened along the* φ *coordinate*: 1 - *field lines start in succession order along R on the inner side of the torus beyond the closed magnetic surfaces (CMS)*; 2 - *the short line begins in the outside region of the torus, beyond CMS. Solid thin lines are the* 2-*wire helical lines*

4. Summary

The present investigations give a general idea about the edge magnetic field structure in both the *l*=2 straight and with the low aspect ratio $A_h=R_o/a_1$≈3.33 toroidal Yamators and enable us to discuss a feasible concept of divertor. The positions of footprints of more that 370 magnetic field lines show that the edge field lines, forming a divertor region in the toroidal Yamator, come to the outside half of the torus, that points to the possibility of creating a discrete divertor. The three-dimensional representation of edge field lines apparently permits a more detailed discussion of the divertor plate geometry.

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