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YAMATOR: High Magnetic-well Value Stellarators

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Abstract

Calculations are extended to the models of new stellarator-type magnetic systems, where the poloidal magnetic field components are formed with the help of 2-wire lines wound round the torus. It is demonstrated that closed magnetic surfaces of large relative volume with a magnetic well reaching a few tens of percent, can be formed in these systems, including module types.

Keywords:

stellarator, 2-wire line, magnetic surface, numerical calculations, magnetic well, module system

1. Introduction

Following the concepts of the magnetohydrodynamic plasma stability theory, it is expedient that the plasma-confining magnetic configuration should have a deep average minimum of the magnetic field B, i.e., a magnetic well $(-U)$ as large as possible. As regards the magnetic systems capable of confining plasma at steady-state operation, a possibility of creating such configurations was considered time and again (see, for example, references in [1]) and by now the search for them still remains rather urgent. This report presents some recent numerical calculations for a new magnetic system [2] having a high magnetic well value and hereafter referred to as YAMATOR. 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 winding is done in such a manner that the wires of each of a 2-wire line with equal and opposite currents I have the same pitch L of winding 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 distance between the wires of the line. The number of 2-wire lines forming the YAMATOR magnetic system determines its polarity l.

2. Linear Configuration

The primary notion of the magnetic field structure in a helical system can be generally formed with the help of a liner approximation. In this case, the magnetic field has the helical symmetry and can be described analytically [3,4]. If $(2\pi a_2 / L)^2 << 1$, then in accordance with [4], one can determine the magnetic surface function $\Psi(r,\theta)$ in the straight YAMATOR system with any polarity l. In particular, for the $l = 1$ system $\Psi(r,\theta)$ has the form:

$$\Psi(r, \vartheta) = \pm \frac{\pi}{L} B_0 r^2 - \frac{\mu_0 I}{2\pi} \ln \frac{1 + (r / a_1)^2 - 2\,(r / a_1)\cos\Theta}{1 + (r / a_2)^2 - 2\,(r / a_2)\cos\Theta}, \qquad (1)$$

Here r, θ, ζ are the cylindrical coordinates, $\Theta = \theta - 2\pi\zeta/L$, B_0 is the longitudinal magnetic field, μ_0 is the magnetic constant. Figure 1 presents a scheme of the $l = 1$ straight YAMATOR, where the mutual helical current and field directions are indicated. Figure 2a presents the cross-sections of the magnetic surfaces in the $a_2/a_1 = 1.5$ system calculated by eq. (1) with the sign "+" at the right-hand first term (i.e., the magnetic field B_0 direction is coincident with the direction of the magnetic field b_0

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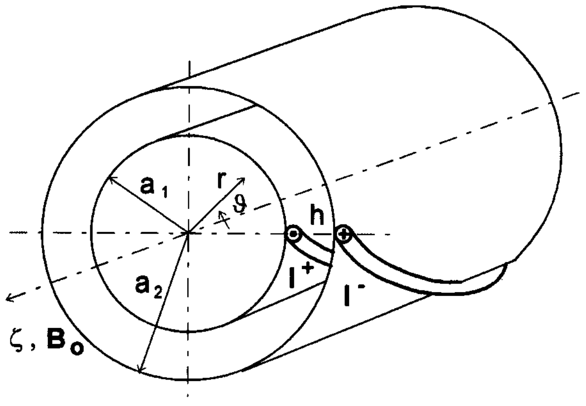

Fig.1 A scheme of the l = 1 straight YAMATOR. The longitudinal magnetic field B_0 coils are not shown.

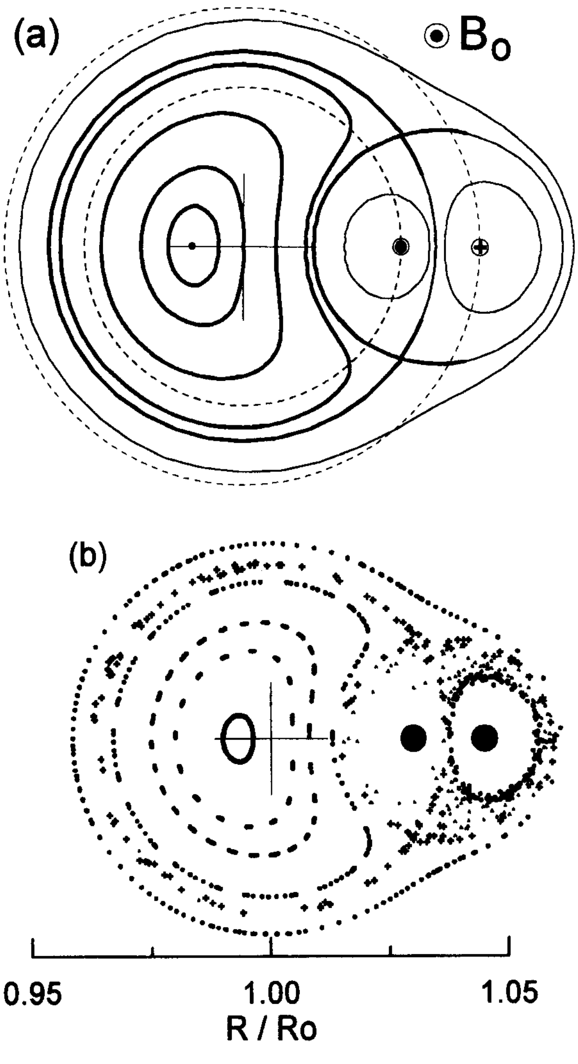

Fig. 2 Magnetic surfaces in the l = 1 a) straight and b) low-toroidicity YAMATORs.

on the geometrical axis of the system, caused by helical current at the a_1 radius, $B_0/b_0 > 0$). The workable magnetic surface region is shown by bold lines. It can be seen that in this region there exist three singular points: one magnetic axis and, in contrast to the l = 1 classical stellarator, two separatrix edges. The ratio B_0/b_0 value determines their location. This configuration is rather well corroborated by numerical calculations for an analogous low-toroidicity ($a_2/R_0 \sim 10^{-2}$) system, Fig. 2b. The case of $B_0/b_0 < 0$ (the sign "–" in (1)) is beyond the scope of the present work.

3. Toroidal YAMATOR Systems

Numerical calculations of toroidal systems were carried out for the following basic model [2]: 2-wire lines were wound on the torus along the helical line $\theta = m\varphi$, θ is the poloidal angle, φ is the toroidal angle, m = 3 is the number of helical pitches along the torus, $h/R_0 = 0.15$ is the distance between the wires of the line, $a_1/R_0 = 0.3$ and $a_2/R_0 = 0.45$ are the aspect ratios of nested tori. The system is plunged into an axisymmetric toroidal magnetic field $B_\varphi = B_0R_0/R$, B_0 is the toroidal magnetic field value on the circular axis of the system, R is the radial position of the observation point, reckoned from the straight axis z. At operating basic conditions the controlling transverse magnetic field is $B_z = 0$. The model allows a simple transition to the torsatron system if B_0 and the inner (or outer) helical current I are put to zero. This circumstance has been used to test the magnetic well value. The result of comparison agrees well with the known literature data.

The l = 1, 2 systems have already been considered in ref. [2]. Here we outline the results concerning the l = 3,4 YAMATOR systems. Figure 3 shows the configuration of one of the magnetic surface cross-sections ($\varphi = 0$) in the l = 3 system for the $B_z = 0$, $B_0/b_0 = 3.33$, and Figure 4 shows the same in the l = 4 system for $B_z = 0$, $B_0/b_0 = 3.75$. It is seen from the figures that, as in l = 1,2 systems, there are inner and outer closed magnetic-surface domains. As in l = 1,2 systems, the shape and position of the outer domain magnetic surfaces are almost independent of toroidal angle φ. The properties peculiar to these surfaces are a very small rotational transform angle, $\iota \sim 10^{-2}$ (from here on ι unit measure is 2π) and the magnetic hill ($+U$), increasing as the average magnetic-surface radius increases. So, the main parameters of the outer domain magnetic surfaces are not adequate for the stellarator experiment. Such an outer domain does not exist in straight YAMATORs. Figure 5 shows that the parameters of the inner domain

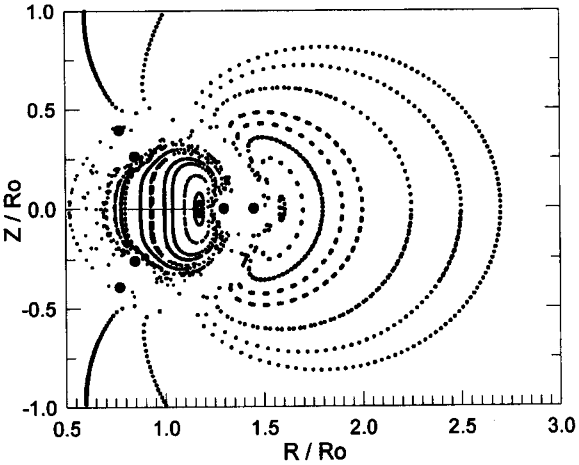

Fig. 3 Magnetic surface cross-sections at $\varphi = 0$ in the l = 3 toroidal model of YAMATOR.

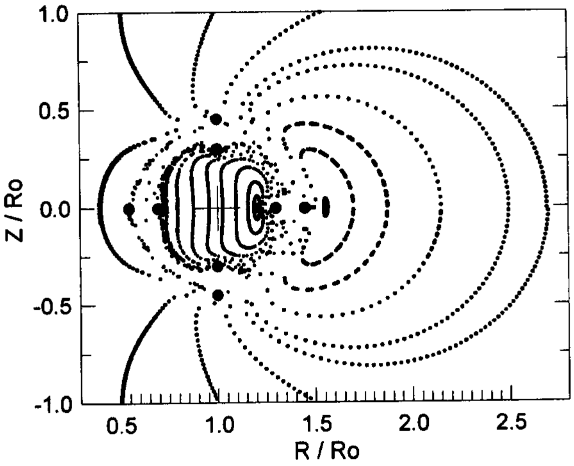

Fig. 4 Magnetic surface cross-sections at $\varphi = 0$ in the l = 4 toroidal model of YAMATOR.

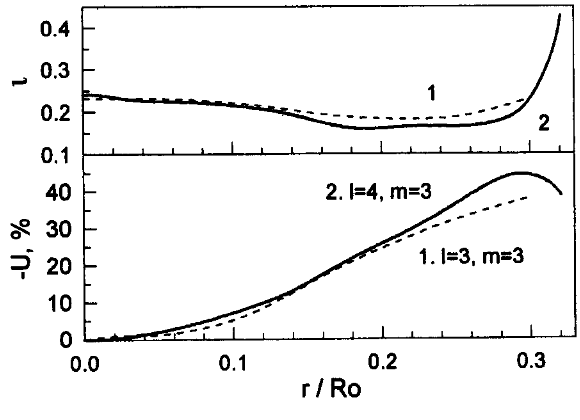

Fig. 5 The rotational transform angle and the magnetic well ($-U$) versus the average magnetic-surface radius r/R_o in the l = 3, 4 YAMATOR systems.

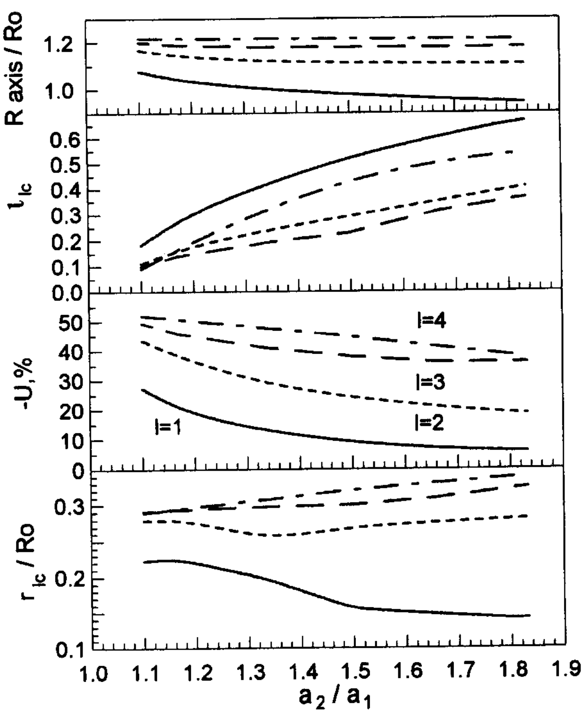

Fig. 6 Radius R_{ax}/R_o of the magnetic axis at $\varphi = 0$, LCMS rotational transform angle ι_{lc}, magnetic well (–U) and LCMS average radius r_{lc}/R_o versus the ratio of one helical coil minor radius to another a_2/a_1, where a_1 = const.

magnetic surfaces meet the requirements for stellarator experiment. In the $l = 3$ system, $(-U) = 38\%$, $\iota = 0.25$ can be attained, the $l = 4$ system provides $(-U) = 45\%$ and ι increases from 0.25 to 0.4 at the last closed magnetic surface (LCMS).

4. Effect of the Parameter *h*

In the YAMATOR systems there is a parameter h, i.e., spacing between the wires of the 2-wire line, which has no analogy in conventional stellarator magnetic systems. Its value determines the ratio of one helical coil minor radius to another a_2/a_1, and thus governs the YAMATOR magnetic system design. Figure 6 shows the LCMS parameters as functions of the ratio a_2/a_1 (a_1 = const.) for l = 1,2,3,4 systems at $B_z = 0$, $B_0/b_0 = 1.0$, 2.5, 3.33, 3.75, respectively. As the parameter h decreases, the magnetic well appreciably increases and the LCMS rotational transform angle ι_{lc} decreases; this is accompanied by the increase of the magnetic axis radius R_{ax}/R_0 ($\varphi = 0$ cross-section), and the rotation of field line slows down mainly at the inner parts of the magnetic surfaces. From Figure 6 it also follows that in

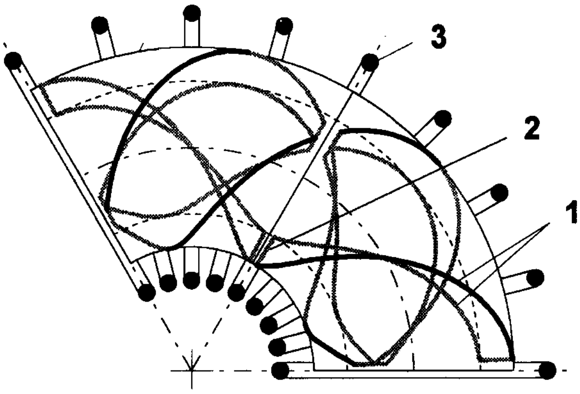

Fig. 7 Top view of the six-module version of the $l = 3$, $m = 3$ YAMATOR (third part): the 2-wire line segment, 1; the radial current-carrying jumper, 2; toroidal field coil, 3.

the YAMATOR system the magnetic well growth is not accompanied, as it takes place in conventional stellarator systems, by an essential loss of the LCMS volume. If $(-U)$ increases (h decreases), the average LCMS radius r_{1c}/R_0 increases in $l = 1,2$ systems and varies only slightly in the $l = 3,4$ systems. If the transverse controlling magnetic field is applied ($B_z \neq 0$), the behavior of the LCMS average radius relative to the magnetic well value is similar.

5. Module YAMATOR System

It has been indicated earlier [2] that a simple realization of a module version of the YAMATOR system consists in joining the 2-wire line segments 1 on the module ends by means of radial current-carrying jumpers 2 of length h (see Figure 7). The jumper currents at the adjacent ends of modules placed in series are equal and opposite. So, the magnetic field perturbations caused by these radial currents seem to be compensated very well, at least for the case of filament-like conductors considered here. Indeed, numerical calculations of a six-module version of the $l = 3$ YAMATOR system at basic operating conditions with the intermodule toroidal angular distance $\Delta\varphi = 4°$ have not shown any appreciable disturbances of the magnetic surface configuration or its parameters.

6. Summary

The main special feature of the new magnetic systems is the possibility to form on their base a toroidal magnetic field with a large average magnetic well ($-U \sim a_l/R_0$). Its value rises as polarity l increases, and for a given l it can still be increased if the parameter $h << a_l$. In a real YAMATOR these methods to adjust the magnetic well value will have a natural limitation due to the finite size of current-currying conductors, this being aggravated by an increasing configuration toroidicity. There is another limitation caused by the rotational transform angle value acceptable for stellarator experiment, since this angle always decreases as the magnetic well grows. The other characteristic feature of the YAMATOR systems is a great volume of the magnetic surfaces, especially in $l = 2,3,4$ systems with a low h value. Both the features seem to be very attractive for the commercial fusion reactor on condition that the first wall problem is finally solved. However, to support this suggestion, comprehensive theoretical, experimental and engineering investigations must be done. The nearest step includes the study of the influence of finite-size conductors on the magnetic configuration in the real YAMATOR, elucidation of the possibility to construct an effective divertor in it, and the neoclassical transport loss estimation.

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