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CONCERNING TOPOLOGY OF MAGNETIC SURFACES OF URAGAN-2M STELLARATOR

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We present and discusses the magnetic surface structures of different Uragan-2M stellarator plasma configuration modes, where large magnetic islands or their remains at the edge of the plasma volume, thus, will lead to deterioration of performance control. The VMEC code is adopted for Uragan-2M in ideal l=2, m=4 stellarator approach without distortions introduced by feeding connectors. This code can be used in magnetic configurations where large core islands are absent.

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INTRODUCTION

Previous theoretical investigations and experiments show that perturbing fields of various types can significantly distort the magnetic configurations of fusion devices (particularly pure 3D ones of various stellarator type). Magnetic islands are the part of the divertor configuration in the modern fusion devices and future reactor systems. Those structures are necessary to control plasma-wall interactions [1-4], and also to provide an efficient control of plasma particle and heat removal [5-8].

The ideal topology of the magnetic surfaces without magnetic islands and stochastic layers is desirable for better plasma confinement. On the other hand, magnetic islands can play a positive role in the stellarator plasmas. For example, rather large magnetic islands at the plasma periphery can be used as the island plasma divertor (W-7X, LHD) [5, 25]. Transport barriers can be formed in vicinity of rational surfaces or small islands and can lead to the confinement improvement (TJ-II) [26, 27]. Some distortion of the ideal structure of the magnetic surfaces at plasma periphery can be created by externally applied 3D perturbative field for the plasma discharge control [24].

In the case of torsatrons with a small number of magnetic field periods (Uragan-2M), where the toroidal magnetic field plays a decisive role in the formation of closed magnetic surfaces, it often appears difficult to create a helical magnetic edge structure which have minimum input on the vacuum vessel surface. For most experiments (which were focused on RF plasma production and wall conditioning by RF discharges) the main goal of the plasma experiments is to avoid those magnetic field perturbations or shift them outside the main plasma volume.

The conditions and investigations needed to justify the edge islands (divertor) concept for the stellarator been adequately formulated in refs. [3]. For previous years Uragan-2M research priority are the investigations into: (a) the magnetic field structure, (b) the localization of O- and X-points of the islands outside the last closed magnetic surface, and (c) the effect of perturbation fields on the islands and the geometry of flux bundles in the vicinity of islands and ergodic regions. The impact of the ergodic region on the divertor arrangement is the problem common for both the helical systems and the tokamaks [6-8]. However, in the case of Uragan-2M, the main difficulties for the field structure congruency for all toroidal field periods are the errors due to the feeding conductors. The topology of the vacuum magnetic fields is calculated using Biot-Savart's Law from all helical, toroidal and poloidal field coils discretized into finite sized filaments. The island free configurations could be found numerically and confirmed experimentally by introducing some additional current in the vertical field correction coils.

THE MAGNETIC FIELD MAIN PARAMETERS FOR THE URAGAN-2M STELLARATOR

The Uragan-2M stellarator (IPP, KIPT) is a torsatron with an additional toroidal magnetic field. It has the following characteristics: the major radius R_0 = 1.7 m and the minor radius a_{vc} = 0.34 m of the toroidal vacuum chamber; the helical winding with l = 2 and the number of magnetic field periods m = 4; 16 toroidal field coils; 8 compensating vertical field coils and 4 correcting field coils. The magnetic configuration and the structure of the facility, the status and experimental program of the torsatron Uragan-2M having an additional toroidal magnetic field B_T have been described in reasonable detail in refs. [9-16].

One can summarize previous Uragan-2M magnetic configuration research as nontrivial from the standpoint of edge plasma position (divertor) implementation, because: (a) practically at all configuration modes the separatrix of the natural helical magnetic divertor cannot fall within the vacuum chamber dimensions; (b) at numerous possible working modes, the plasma, which diffuses from the confinement volume, must mainly stream along the magnetic field lines of a wide ergodic region to the vacuum chamber wall for the apexes of elliptically-shaped magnetic surfaces; (c) in most cases, the separatrix of the chain of islands and its neighborhood are generally broken at the edge of the confinement volume; (d) besides, as demonstrated numerically in refs. [1-4, 6, 8], the edge island structures can be cut off by the vacuum chamber wall, as also, can be broken up due to perturbations or can disappear in a natural way with a change in the vertical magnetic field value. This means that by varying this field one can easily control, within certain limits, the divertor geometry from outside, and also in time.

SPECIAL FEATURES OF THE MAGNETIC CONFIGURATIONS FOR THE URAGAN-2M

The magnetic configuration modes in the Uragan-2M are determined by variation of the parameter $k_\varphi = B_h/(B_h + B_T)$ [9, 14], which represents the ratio of the toroidal (longitudinal) magnetic field of the helical winding B_h to the total toroidal magnetic field B_0, where $B_0 = (B_h + B_T)$, and also by the ratio of the mean vertical magnetic field to the toroidal magnetic field on the geometrical axis of the torus $<B_\perp/B_0>$. The figure at page 68 in ref. [10] and Fig. 3 in ref. [11] show, that with k_φ changing from 0.28 to 0.375, the mean radius of the calculated closed magnetic surfaces decreases, and the rotational transformation angles (hereinafter we will express it as 2π normalized value $i = i/2\pi$) increase from i = 0.25 up to i = 0.52 on the magnetic axis, and from i = 0.3 up to i = 0.7 on the last closed surface.

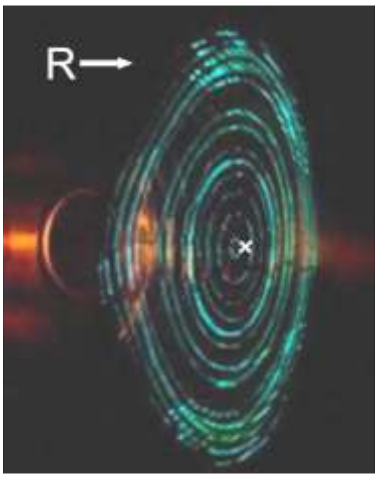

Fig. 1. Magnetic surface structure at the configuration with vertically elongated plasma for mode with k_φ = 0.285, R_{ax}=163.4 cm

It is very clear that, the minor radius of the toroidal vacuum chamber prevents the mean radius of the magnetic surfaces from being greater than a = 0.225 m, even if the magnetic axis of the surfaces lies in the neighborhood of the minor axis of the torus (R_{ax}=R_0=1.7 m). The elliptical magnetic surfaces are always cut off by the vacuum chamber at the $k_\varphi \le 0.28$ modes, and also, with vertical magnetic field increase and decrease (i.e., with magnetic axis shift outwards or inwards from the minor axis of the torus). After restart of the Uragan-2M operation in 2006 the new set of the magnetic field structure measurements were performed. For experimental investigation of closed magnetic surface structures in the Uragan-2M torsatron, the earlier-tested scanning luminescent rod technique has been used. The most comprehensive description one can find in refs. [12, 15]. In the those experiments the stationary magnetic field on the geometrical axis of the torus was equal to B_0= 0.1 T. Some results of the measured magnetic configuration are presented in the Fig. 1, the (x) sign indicates the position of the geometrical axis of the torus.

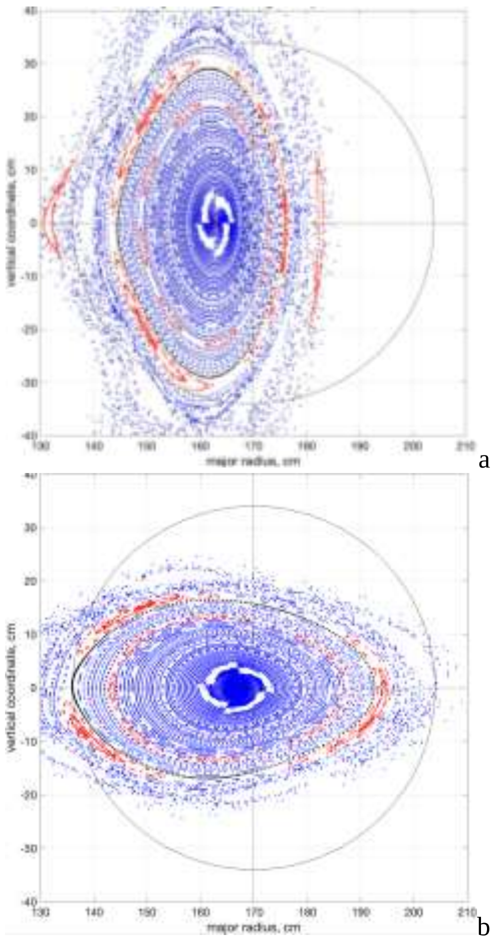

Fig. 2. Magnetic surface structure for Uragan-2M in the case of vertically (a) and horizontally (b) elongated plasma: k_φ = 0.285, B_0=0.1T, R_{ax}=163.2 cm, I_h=132 kA, I_T=-82 kA, I_c=0.0 kA

For the magnetic field description, the numerical code uses the coordinates of design helical-windings or stellarator coils and also of toroidal, compensating and correcting field coils of the Uragan-2M torsatron.

The code also took into account the design-provided geometry of helical winding detachable joints and current feed leads. The total number of current filaments for every type of coils are as follows: (a) helical coils – 400; (b) toroidal field coils – 480; (c) poloidal (vertical) field coil – 100; (d) correction field coil – 80. The U-2M magnetic system is water cooled. Tpy numerical modeling of a large number of variants showed that the perturbations introduced by the detachable joints and current feeds shows the formation of island structures with $i = 1/3$, 2/5, 2/7, 3/8, 1/2, etc. in addition to the previously known island structures with $i = 4/7$, 4/6, 4/5, 8/9, etc., (see, for example, refs. [18, 19]. It has also indicated the magnetic surface deformation, the violation of periodicity and helical symmetry of magnetic surfaces in the configuration [12, 17-22]. The numerically predicted islands and configuration perturbations were confirmed by magnetic surface measurements in a wide range of modes with changes in k_φ and in the vertical magnetic field $<B_\perp/B_0>$ [27-31].

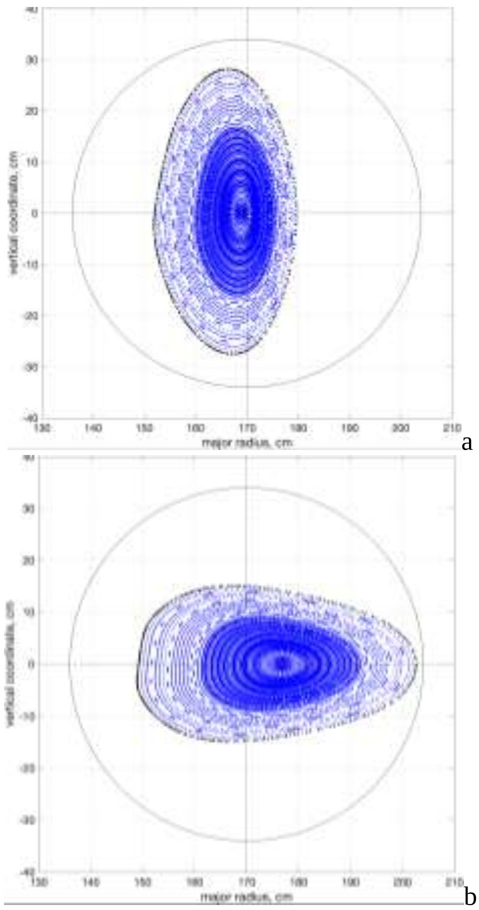

Fig. 3. Magnetic surface structure for Uragan-2M in the case of vertically (a) and horizontally (b) elongated plasma: $k_\varphi = 0.285$, B_0=0.1 T, R_{ax}=168.4 cm, I_h=132 kA, I_T=-82 kA, I_c=3.2 kA

The numerical calculation for the k_φ that changes from 0.38 down to 0.34, the largest islands with $i = 1/2$ shift, simultaneously growing in size, from the magnetic axis towards the edge of the closed magnetic surface region. In the $0.28 < k_\varphi = 0.285$, the large islands with $i = 1/3$ also move to the periphery of the magnetic field structure inside and outside the vacuum chamber, please see red colored closed curves (magnetic islands) in Fig. 2. The shift of the islands to the edge generally results in their breakdown. The possibility of controlling the profile of the rotational transformation angle and the mean radius of the last closed magnetic surface through variation of the vertical magnetic field showed in refs. [17-22]. In this article we presented the numerical calculation for two modes only. As an example, we consider the mode where the $k_\varphi = 0.285$ (almost 'fat configuration').

However, in case of $k_\varphi \le 0.31$ configuration modes it must be understood that in the toroidal cross-sections with vertical arrangement of elliptical-shape magnetic surfaces on the inner half of the torus, the islands at the edge may appear to be in contact with the vacuum chamber wall and may be cut off by it at two apexes of the ellipse. For $k_\varphi \le 0.32$, the vacuum chamber wall also restricts the variation range of the controlling vertical magnetic field, because the horizontally lying elliptical-shape magnetic surfaces may be cut off. It can be inferred by the decrease in the radius of the region of closed magnetic surfaces fitting in the vacuum chamber, see the ends of curves. The $i = 1/3$ island structures, measured in [27, 28], where toroidal magnetic field periods, have exhibited the phase shift of the islands, which results from the violation of the field-period helical symmetry of the magnetic configuration due to the influence of helical winding detachable joints.

Two modes with the magnetic islands of resonances $i = 1/3$ and 2/5 at the edge (see Fig. 1) have been investigated in detail.

The characteristic property of these two magnetic surface structures is the location of the islands having the largest radial dimensions mainly in the neighborhood of the apexes of elliptically-shaped magnetic surfaces. In the poloidal cross sections of the torus for the vertically elongated plasma (Fig. 4), the vacuum chamber wall crosses one large island only on the inside of torus. In the cross sections with vertical arrangement of elliptically shaped magnetic surfaces the islands together with the neighborhood of their separatrix touch the vacuum chamber wall at two apexes of the ellipse. Here, the vacuum chamber wall cuts off mainly the separatrix region around the islands. The islands change their shape along the torus. The island structures with $i = 1/3$, determined in these sections, have exhibited the phase shift of the islands. As is known, this phase shift of the islands is also due to the violation of the field-period helical symmetry of the magnetic configuration. For the two modes under consideration the numerical computation confirms the phase shift of the islands both inside and at the edge of the closed surface structure.

For arranging the island divertor, the knowledge of the phase shifts of the islands will be helpful to make the right choice of the site, working plasma access ports. This is particularly significant because of a permanent shortage of convenient access ports due to the usage of numerous diagnostics and heating techniques.

In another variant of the plasma configuration, where the islands are located inside, but in close vicinity to the last closed magnetic surfaces. To suppress those islands, a movable local limiter has already been installed and tested at the Uragan-2M [23].

Finally, we must point out that for the magnetic configuration mode $k_\varphi = 0.285$ with no correction current (I_c=0.0 kA) the i = 1/3 resonance islands at the edge are no longer at the ellipse apexes.

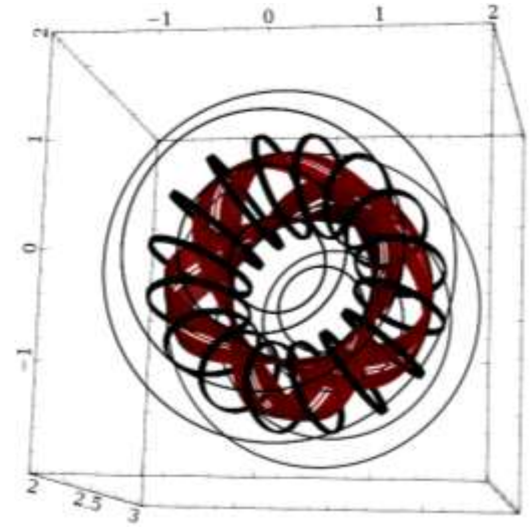

Fig. 4. Simplified set of Uragan-2M magnetic coils

SIMPLIFIED MAGNETIC COILS FOR VMEC CODE

Recently the computational search for the configuration modes of the Uragan-2M stellarator [17, 19-22] has been performed. As a result, it is possible to formulate island divertor concept. The earlier developed code was updated and has been applied to fulfill necessary conditions for VMEC code input. The variational moments equilibrium code (VMEC) is the most widely used to evaluate 3D ideal-MHD equilibria in stellarators [28].

It is well known that the influence of the feeding conductors can cause large magnetic islands formation in the plasma core region.

Such configurations cannot be modeled by the means of the VMEC code. In other usual configurations and in configurations with additional plasma shift outside the large magnetic islands are absent in the plasma core. These magnetic configurations can be modeled by the VMEC code. Since we are planning to use VMEC code for the magnetic topology distortion due to plasma current and pressure influences, we need to run VMEC in the free plasma boundary conditions. The idealized magnetic coils topology of l=2, m=4 stellarator case without feeding conductors is produced (see Fig. 4) and imported for the code VMEC. The total number of current filaments for every type of coils are as follows: (a) helical coils – 20; (b) toroidal field coils – 48; (c) poloidal (vertical) field coil – 8; (d) correction field coil – 4.

The last close magnetic surface was extracted from the accurate Uragan-2M magnetic surfaces calculations data which is shown in Fig. 2. This last close magnetic surface is used as input data for the VMEC code as a first approach of the last close magnetic surface topology in the free boundary run options. The first VMEC result of the magnetic surfaces calculation without plasma pressure and current distortions are shown in Fig. 5 for the $k_\varphi = 0.285$ case.

Thus, the code VMEC is adopted and can be further used for Uragan-2M studies in some magnetic configurations where large core islands are absent.

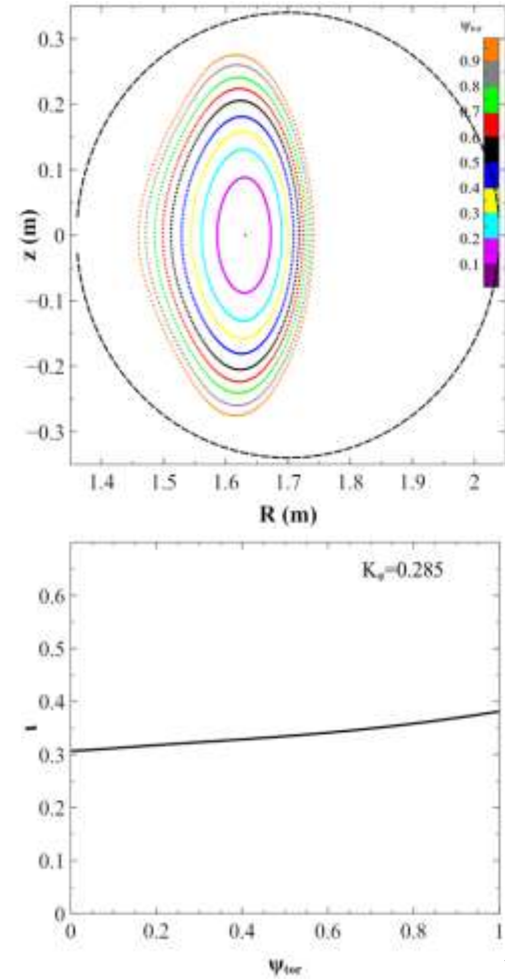

Fig. 5. Magnetic surfaces for vertically elongated plasma (a) and corresponding rotational profile (b) in k_φ = 0.285 configuration calculated by code VMEC

CONCLUSIONS

Some computational investigations have enabled us to find several modes of configurations with the islands of resonances at the rotational transformation angles i = 1/3, 3/7, 2/5, 1/2, 4/5, which lie mostly outside, nearby and inside the last closed magnetic surface. The configuration mode which under consideration is: $k_\varphi = 0.285$, $\langle B_\perp/B_0\rangle \approx 1.45$.

The calculated magnetic structure shows almost same topology which was measured previously in the low-density plasma discharge with the scanning luminescent rod procedure. Those measurements demonstrate the possibility of the island divertor implementation. It was shown that several islands or their remains exist at the edge of the closed magnetic surface region, i.e., at the plasma boundary.

Fast, robust, widely used throughout the word VMEC-code assumes nested magnetic flux surfaces, magnetic islands and chaotic regions of the magnetic field structure must be ignored. A simplified (ideal) magnetic coil geometry (i.e. no coil misalignment or other deformations such as input joints) is considered.

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ЩОДО ТОПОЛОГІЙ МАГНІТНИХ ПОВЕРХОНЬ СТЕЛАРАТОРА УРАГАН-2М

Р.О. Павліченко, М.Б. Древаль, В.Г. Котенко, А.М. Шаповал, Г.Г. Лесняков, А.Р. Тітаренко

Представлено та обговорено структури магнітної поверхні для різних режимів конфігурації плазми стеларатора Ураган-2М, де великі магнітні острівці або їхні залишки на краю об'єму плазми призводять до погіршення якості керування. Код VMEC прийнято для Урагану-2М в ідеальному наближенні стеларатора l=2, m=4 без спотворень, що вносяться живильними з'єднувачами. Цей код можна використовувати в магнітних конфігураціях, де відсутні великі острови осердя.