FEASIBILITY OF CREATING AN ISLAND DIVERTOR IN THE URAGAN-2M TORSATRON

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The concept of an island divertor appears the only suitable idea that may be helpful to make up for the absence of a natural helical divertor in the magnetic configuration. In this context, the paper presents and discusses the measured and calculated magnetic surface structures of different configuration modes, where large magnetic islands or their remains at the edge of the plasma volume may be used for experimental implementation of the island divertor.

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INTRODUCTION

The divertor structure is necessary to control the plasma-wall, plasma-target interactions [1, 2], and also to provide an efficient monitoring of particles [3, 4]. In stellarators, where the toroidal magnetic field plays a decisive role in the formation of closed magnetic surfaces, it is every so often difficult to create a helical magnetic divertor structure. The conditions and required investigations to justify the island divertor concept for the stellarators of this kind have been adequately formulated in refs. [1, 2]. Of first priority [1] are the studies of the magnetic field structure, the localization of O- and X-points of the islands outside the last closed magnetic surface, the effect of perturbation fields on the islands and geometry of flux bundles in the vicinity of islands and ergodic regions.

1. SPECIAL FEATURES OF THE ISLAND DIVERTOR CONCEPT FOR THE "URAGAN-2M" TORSATRON AND THE WORK OBJECTIVE

The Uragan-2M torsatron has the following characteristics: major radius R=1.7 m and minor radius of the toroidal vacuum chamber a_{vc}=0.34 m; 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, structure of the facility, status and experimental program of the torsatron "Uragan-2M" having an additional toroidal magnetic field have been described well enough in papers [5-8].

The magnetic configuration of the Uragan-2M torsatron having an additional toroidal magnetic field looks complicated from the standpoint of divertor feasibility, namely:

- practically at all configuration regimes, suitable for operation with the plasma, the separatrix of the natural magnetic divertor cannot fall within the vacuum chamber dimensions;
- at numerous possible working regimes, the plasma, which diffuses from the confinement volume, must mainly stream along the magnetic field lines of a broad ergodic region to the vacuum chamber wall for the apexes of elliptically-shaped magnetic surfaces;
- practically in most cases, the separatrix of the islands and its vicinity are generally disrupted at the edge of the confinement volume, and then this vicinity represents the distributed regions of the preferential plasma outflow to the vacuum chamber wall;
- besides, the island structures can be cut off by the vacuum chamber wall; they can break down due to perturbations or disappear in a natural way, and these processes can be controlled through vertical magnetic field variation. The magnetic configuration modes in the Uragan-2M are determined not only by variation of the parameter k_φ, which represents the ratio of the toroidal magnetic field of the helical winding to the total toroidal magnetic field, but also by the ratio of the average vertical magnetic field to the toroidal field on the geometrical axis of the torus $\langle B_\perp/B_0 \rangle$.

In another variant of the concept implementation, where the islands are located inside, but in close vicinity to the last closed magnetic surfaces, one can use a movable local limiter, already created and trial-tested at the Uragan-2M [9].

That is why the only concept that is suitable to make up for the absence of the natural helical divertor in the Uragan-2M torsatron is the concept of the island divertor. This concept should rely on such configuration modes when large-in-size magnetic islands or their remains exist at the edge of the closed magnetic surface region, i.e., at the plasma boundary.

The present work has reduced to finding (both experimentally and numerically) out of a vast number of possible regimes those several regimes with the islands at the edge, which would decide the issues of island divertor creation.

2. MAGNETIC SURFACE STRUCTURES MEASURED AT THE MODES THAT MEET THE CONCEPT OF THE ISLAND DIVERTOR

For experimental investigation of closed magnetic surface structures in the Uragan-2M torsatron, the earlier-tested scanning luminescent rod technique has been used [7, 8]. The scanning luminescent rod was placed in the poloidal section of the vacuum chamber between the toroidal field coils at the site, where the elliptically-shaped magnetic surfaces were arranged vertically. In the section, where the magnetic surface measurements were made, on the vacuum-chamber inner surface two light-emitting diodes (LEDs) with the known interspace between them were installed. The horizontally-movable electron gun was placed in the vacuum chamber section, which was clear of the measurement section. It injected 40 to 50 eV electrons on the magnetic field lines. In the present studies the stationary magnetic field of the geometrical axis of the torus was equal to B_0= 0.1 T.

Before everything else it should be noted that during the experiments a unique photograph was taken, which well illustrates the operation of the island divertor (Fig. 1).

The peculiarity of the image obtained lies in the fact that it displays two concurrent processes. If the luminescent rod scans the poloidal section of the magnetic configuration, where the last closed surface is continuously filled up with electrons from the small gun, then all round the chamber section we observe the discharge with a low plasma density, which is caused by the induction electric field associated with magnetic field oscillations. In the figure, the arrow labeled "e-beam" shows the last closed magnetic surface, onto which the electron beam is injected to measure its form. The arrows bearing figures 1, 2, 3 point to three islands of the resonance angle of rotational transform $i/2\pi=1/3$, within which the low-density plasma is confined. The "Sep" arrows show the dark region between the last closed magnetic surface of the confinement volume and the islands, where the separatrix and the field lines in its neighborhood are broken and open, and therefore, there is no confinement of the discharge particles. From now on, in all the figures depicting the measured magnetic surfaces two bright points at the edges of the figure display the position of reference LEDs, and the (+) sign indicated the position of the geometrical axis of the torus.

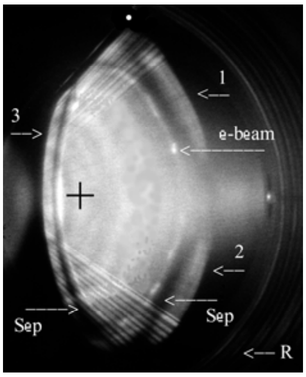

Fig. 1. Visual demonstration of the island divertor operation. The view of the low-density plasma confinement region in the Uragan-2M torsatron: mode $k_\varphi\approx0.295$, $<B_\perp/B_0>\approx1.8$ %; *mean radius of the last closed magnetic surface a≈16.3 cm; thickness of separatrix region Sep≈0.45…2.5 cm; transverse dimensions of islands δ≈2.3-4.7 cm*; *mean radius of O- and X-points of islands r≈19.6 cm*

Below we show the measured Uragan-2M modes of the magnetic configuration with islands at the edge. The modes admit a variety of conditions making possible studies of the island divertor and, later, its efficient use. The changes in the islands with $i/2\pi=1/3$ at the edge of field configurations under two modes controlled by the vertical magnetic field can be seen in Fig. 2–Fig. 8.

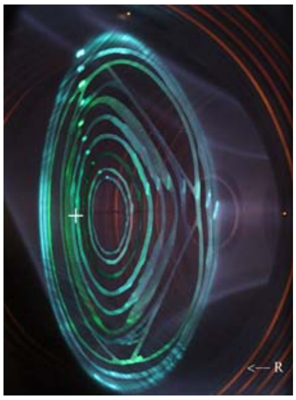

Fig. 2. Magnetic surface structure at the configuration mode with $k_\varphi=0.31$ and $<B_\perp/B_0>=1.85$ %: mean radius of the last closed magnetic surface a≈20.4 cm; three magnetic islands $i/2\pi=1/3$ lie near the edge; mean radius of the island centers (O-points), r≈16.5 cm; magnetic axis displacement from the geometrical axis of the torus Δ≈ -5.7 cm. Hereafter, the (-) sign at the magnetic axis shift shows that the magnetic axis is displaced inwards relative to the geometrical axis of the torus

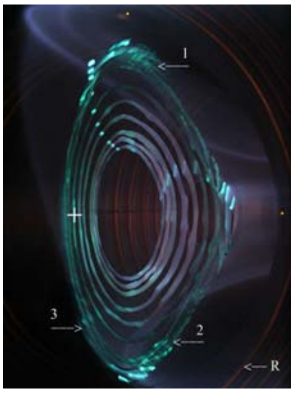

Fig. 3. Magnetic surface structure at the configuration mode with $k_\varphi=0.31$ and $<B_\perp/B_0>=1.14$%: the mean radius of the closed magnetic surface, which is adjacent to three whiskers (1, 2, 3), i.e., remains of the broken magnetic islands with $i/2\pi=1/3$, is a≈17.3 cm; Δ≈-9 cm

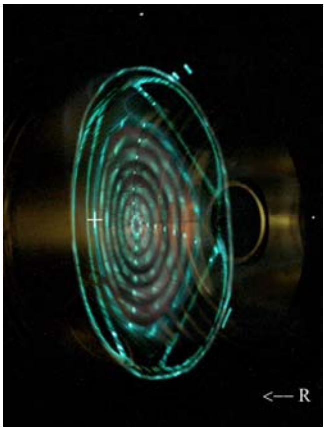

Fig. 4. Magnetic surface structure at the configuration mode with $k_\varphi=0.32$ and $<B_\perp/B_0>=1.58$%: the mean radius of the closed magnetic surface, which is adjacent to the chain of magnetic islands with $i/2\pi=1/3$, is a≈17 cm; Δ≈-6.65 cm; δ≈2.5…5 cm; island lengths are $l_{is}\approx20.6$, 21 and 41 cm; the mean radius of the island centers (O-points) is r≈13 cm

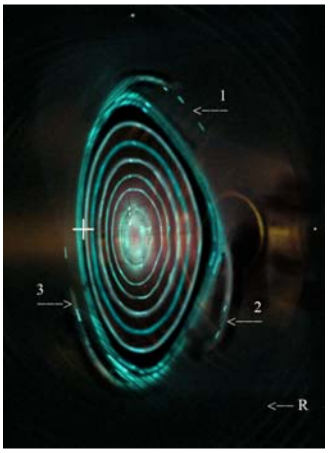

Fig. 5. Magnetic surface structure at the configuration mode with k_φ=0.32 and $<B_\perp/B_0>$=1.34 %: the mean radius of the closed magnetic surface, which is adjacent to three whiskers (1, 2, 3), i.e., remains of the broken magnetic islands with $i/2\pi$=1/3, is $a\approx$14.4 cm; $\Delta\approx$-7.7 cm

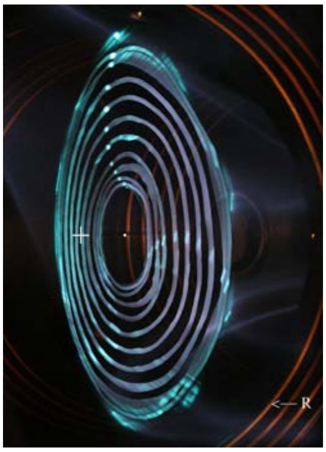

Fig. 6. Magnetic surface structure at the configuration mode with k_φ=0.33 and $<B_\perp/B_0>$=1.92 %: the mean radius of the closed magnetic surface, which is adjacent to two neighboring chains of magnetic islands with $i/2\pi$=2/5 and $i/2\pi$=3/7, is $a\approx$19 cm; $\Delta\approx$-6.4 cm

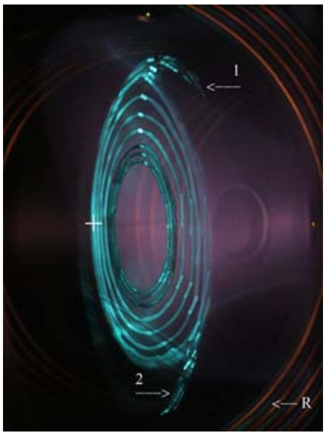

Fig. 7. Magnetic surface structure at the configuration mode with k_φ=0.36 and $<B_\perp/B_0>$=2.03%: the mean radius of the closed magnetic surface, which is adjacent to two whiskers (1, 2), i.e., remains of two magnetic islands with $i/2\pi$=1/2, is $a\approx$14.3 cm; $\Delta\approx$-7.6 cm

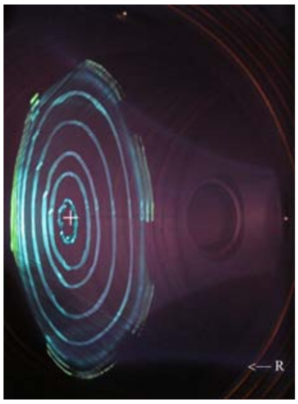

Fig. 8. Magnetic surface structure at the configuration mode with k_φ=0.295 and $<B_\perp/B_0>$=3.21 %: the mean radius of the closed magnetic surface, which is adjacent to a chain of five magnetic islands with $i/2\pi$=2/5, is $a\approx$16.8 cm; $\Delta\approx$+1.0 cm

3. THE NUMERICALLY DETERMINED MODES OF MAGNETIC CONFIGURATION WITH ISLANDS AT THE EDGE

To perform the computational search for the configuration modes that would meet the formulated island divertor concept, the earlier developed code has been applied [10]. In the field description, the numerical code uses real layings of bus bars of helical windings, toroidal, compensating and correcting field coils of the Uragan-2M torsatron. Besides, the code took into account the design-provided geometry of helical winding detachable joints and currentfeed connectors. The consideration of perturbations introduced by the detachable joints and currentfeeds has shown the formation of island structures (in addition to natural ones) with $i/2\pi$=1/2, 1/3, 4/7, 4/6, 4/5, 8/9, etc., the deformation of the magnetic surfaces, the violation of magnetic configuration periodicity and symmetry [7, 10]. The numerically predicted islands and configuration perturbations were confirmed by magnetic surface measurements [7, 8].

Two more regimes with magnetic islands of resonances $i/2\pi$=1/3 and 2/5 at the edge, (Figs. 9 and 10) have been found by the computational method.

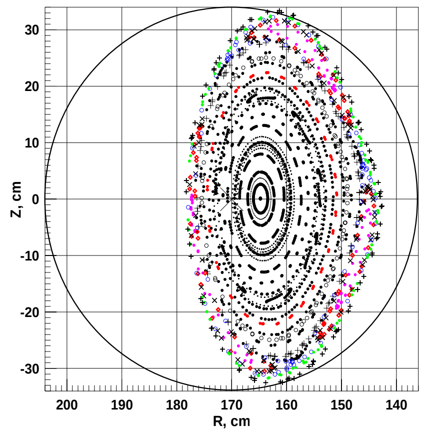

Fig. 9. Magnetic surface structure at the configuration mode with k_φ=0.285 and $<B_\perp/B_0>$=1.45 %: the mean radius of the closed magnetic surface, which is adjacent to a chain of magnetic islands with $i/2\pi\approx$1/3, is a=20.5 cm; Δ=-5.3 cm; $i/2\pi(0)\approx$0.18; $i/2\pi(a)\approx$1/3; $\delta\approx$1.5-4.5 cm; a large angular length of the islands

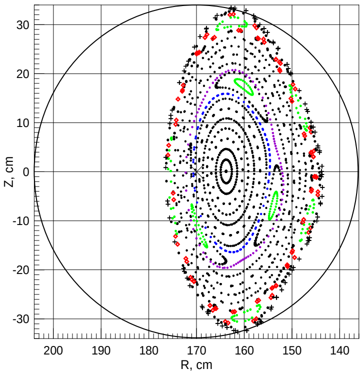

Fig. 10. Magnetic surface structure at the configuration mode with $k_φ$=0.31 and <$B_⊥/B_0$>=1.5 %: the mean radius of the closed magnetic surface, which is adjacent to a chain of magnetic islands with i/2π=2/5, is a≈20 cm; Δ=-6.26 cm; i/2π(0)≈0.25; i/2π(a)≈2/5

The characteristic property of these two magnetic surface structures is the location of the islands having the largest radial dimensions at the apexes of elliptically-shaped magnetic surfaces.

It is pertinent to note that the two mentioned regimes should be complemented with one more configuration mode with $k_φ$≈0.375, calculated in paper [11]. In [11] it was first suggested that the islands with *i*/2π=4/5 could be used for creating the island divertor.

CONCLUSIONS

The experimental magnetic field structure studies by the scanning luminescent rod technique as well as the computational investigations have enabled us to find ten modes of configurations with the islands of resonances at the rotational transform angles *i*/2π=1/3, 3/7, 2/5, 1/2, 4/5, which lie outside the last closed magnetic surfaces. The combination of the low-density plasma discharge with the scanning luminescent rod procedure to measure the magnetic surface has first visually demonstrated the operation of the island divertor. It has also been shown that by varying the vertical magnetic field value in the configuration it is possible to provide the following capabilities for controlling the island divertor operation: i) to cut off the islands by the vacuum chamber wall; ii) to use the remains of the islands already broken down by the existing perturbations; iii) to reduce and suppress the islands. In another variant of the island divertor realization, when the islands are positioned inside and close to the last closed magnetic surfaces, a movable local limiter can be used.

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ВОЗМОЖНОСТИ СОЗДАНИЯ ОСТРОВНОГО ДИВЕРТОРА В ТОРСАТРОНЕ УРАГАН-2М

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Единственной подходящей концепцией, с помощью которой можно восполнить отсутствие естественного винтового дивертора в магнитной конфигурации, является концепция островного дивертора. В этой связи представлены и обсуждаются измеренные и вычисленные структуры магнитных поверхностей разных режимов конфигурации, в которых большие магнитные острова или их остатки на краю плазменного объема можно использовать для экспериментальной реализации островного дивертора.

МОЖЛИВОСТІ СТВОРЕННЯ ОСТРІВНОГО ДИВЕРТОРА В ТОРСАТРОНІ УРАГАН-2М

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Єдиною придатною концепцією, за допомогою якої можна заповнити відсутність природного гвинтового дивертора в магнітній конфігурації, є концепція острівного дивертора. У зв’язку с цим наведено та обговорюються виміряні й обчислені структури магнітних поверхонь різних режимів конфігурації, у яких великі за розміром магнітні острови або їх залишки біля краю плазмового об’єму можна використати для експериментальної реалізації острівного дивертора.