TORSATRON U-2M MAGNETIC SURFACES WITH ENHANCED MIRROR RATIO

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Existence of closed magnetic surfaces with enhanced mirror ratio value and mirror region longitudinal size in a model of the combined magnetic system is shown by numerical calculations. The calculation model contains the *l=2* polarity torsatron *U*-2M magnetic system with the additional toroidal magnetic field coils and the mirror-type magnetic system. The mirror-type magnetic system is realized by switching off two adjacent additional toroidal magnetic field coils.

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INTRODUCTION

As a fusion neutron source for the sub-critical hybrid nuclear reactor [1] in the paper [2] has been proposed the magnetic system combination, including a stellarator-type and a mirror-type magnetic systems. In the paper [3] as a stellarator-type magnetic system the magnetic system of the torsatron *U*-2M [4] was considered. The system along with the helical coils comprises the additional toroidal magnetic field coils. The combined with stellarator-type magnetic system the mirror-type magnetic system was realized by switching off one of the additional toroidal magnetic field coils.

In this paper the magnetic field of the combined magnetic system is studied where the combined with stellarator-type magnetic system the mirror-type magnetic system is realized by switching off two adjacent additional toroidal magnetic field coils. The purpose of the study is to estimate the possibility to form the closed magnetic surface configuration with enhanced mirror ratio value and mirror region longitudinal size in the torsatron *U*-2M device.

1. CALCULATION MODEL

The main geometrical characteristics of the calculation model are similar to the design characteristics of the *U*-2M torsatron magnetic system [3-5]. The model comprises 16 the additional toroidal magnetic field coils. The mirror-type magnetic system is realized by switching off two adjacent additional toroidal magnetic field coils 1 and 16 (Fig. 1).

The following technical characteristics of the real helical coils and the additional toroidal magnetic field coils were counted in the calculation:

- toroidicity a/R_o=0.2618, a is the minor radius of the torus (average radius of helical coils), R_o is the major radius of the torus;
- l=2 is the polarity;
- m=2 is the number of helical coil pitches along the length of the torus;
- there are 20 conductor turns in each helical coil;
- each helical coil is separated by diagnostic gap into two equal parts, each part comprises 10 conductor turns;
- the central line of the diagnostic gap is the helical base line marked on the torus according to the equi-inclined winding law $\theta(\varphi)$=2 arctg (1.3074 tgφ), where φ is the toroidal angle and θ is the poloidal angle. The base line is the helical line, along which a supporting structure of the helical coil is assembled;
- the conductor turns are packed turn by turn symmetrically relative to the helical base line on the both side of the diagnostic gap;
- the average radius of the additional toroidal magnetic field coils is a_c/R_o=0.4 (the radial thickness of coil winding 0.113R_o is not taken into consideration);
- the coils have cylindrical form, the cylinder height h/R_o =0.086;
- the calculation model of the coil comprises 3 turns of the thin conductor. The plane of the central turn of the coil model agrees with meridian (poloidal) plane of the torus. The rest 2 turns of the coil lie in the end planes, which are parallel to the plane of the central turns of the coil.

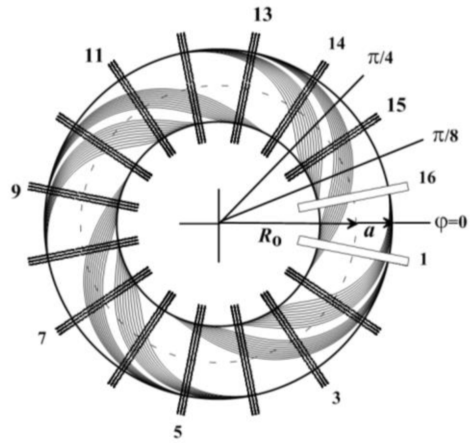

Fig. 1. Top view of the magnetic system of the l=2 torsatron U-2M calculation model. The positions of two adjacent switched off coils 1, 16 are indicated

In the present calculations, the transverse compensating magnetic field B_z is considered as uniform. The magnetic surface configuration in the torsatron with an additional magnetic field coils is also affected by the parameter $K_\varphi=1/(1+B_o/b_o)$, where B_o is the value of the additional toroidal magnetic field on the circular axis of the torus, b_o is the amplitude of the longitudinal component of the magnetic field generated by the helical coils on the circular axis of the torus.

2. RESULTS OF CALCULATIONS

2.1. MAGNETIC SURFACES

Fig. 2,a,b show the poloidal cross-sections of the magnetic surfaces for the calculation models. The cross-sections are spaced round a toroidal angle φ=0, π/8, π/4 and π (see Fig. 1). In the figures, the dashed circle is the cross-section of a torus a/R_o=0.2618 with traces of the conductor turns of the helical coils (large black dots). The inner circle shows the cross-section of the vacuum chamber (the minor radius a_v/R_o=0.2) in the *U*-2M torsatron.

Fig. 2,a shows the cross-sections of the initial (undisturbed by switching off the coils 1, 16) magnetic surface configuration. It is seen from the figure the initial magnetic surface configuration has the plane magnetic axis and the last closed magnetic surface (LCMS) transcending of the torus surface. The mode is realized at the compensating magnetic field value B_z/b_o=0.507 and the additional toroidal magnetic field value B_o/b_o=4 (K_φ=0.2). The magnetic axis has the shape of the circle with major radius R_{ax}/R_o=0.916 lying in the torus equatorial plane. The LCMS average radius is r_{lc}/R_o =0.2. The shape of the magnetic surfaces in the $\varphi=\pi$ cross-section coincides with the shape in φ=0 cross-section. The rotational transform angle (ι in 2π units) is $\iota_{ax}\rightarrow\iota_{lc}$=0.05$\rightarrow$0.25, and there is a magnetic hill in the configuration, *U*=0.09. The mirror ratio ranges within $\gamma_{ax}\rightarrow\gamma_{lc}$=1.01$\rightarrow$1.86, $\gamma=B_{max}/B_{min}$, where B_{max} and B_{min} are the maximum and minimum magnetic field values on the magnetic surface.

In Fig. 2,b the cross-sections of the magnetic surfaces by switching off the coils 1, 16 are presented. It is seen from the figure that the switching off results in a magnetic surface configuration decrease, so the LCMS φ=0 cross-section fits in the vacuum chamber.

The area of the other poloidal cross-section decreases gradually, as it comes nearer to the toroidal azimuth $\varphi=\pi$. The maximum area cross-section S_{max} is in the middle of the coil 1, 16 spacing on the azimuth φ=0, where the LCMS average radius is r_{lc}/R_0=0.11(0.1). For the comparison here and below the magnetic surface parameters in the calculation model with one switched off coil [3] are indicated in brackets. The minimum area cross-section S_{min} is found on the azimuth $\varphi=\pi$, where the LCMS average radius is r_{lc}/R_0=0.062. The ratio S_{max}/S_{min}~3 is the value of the pinch ratio of the magnetic surface configuration.

The magnetic surface poloidal cross-section decrease is accompanied by the gradual decrease of the magnetic axis major radius R_{ax}/R_0, i.e. by the configuration shift inward the torus. The magnetic axis major radius is R_{ax}/R_0=0.941 for φ=0° and R_{ax}/R_0=0.914 for φ=180°.

The values of rotational transform angle, $\iota_{ax}\rightarrow\iota_{lc}$=0.12$\rightarrow$0.18 (0.09$\rightarrow$0.18), and magnetic well, -*U*=0.007 (0.001), do not differ substantially from the corresponding parameters in the calculation model with one switched off coil. The maximum value of the mirror ratio γ on the magnetic surfaces undergoes an appreciable change, $\gamma_{ax}\rightarrow\gamma_{lc}$=2.41$\rightarrow$2.91 (1.56$\rightarrow$2.06).

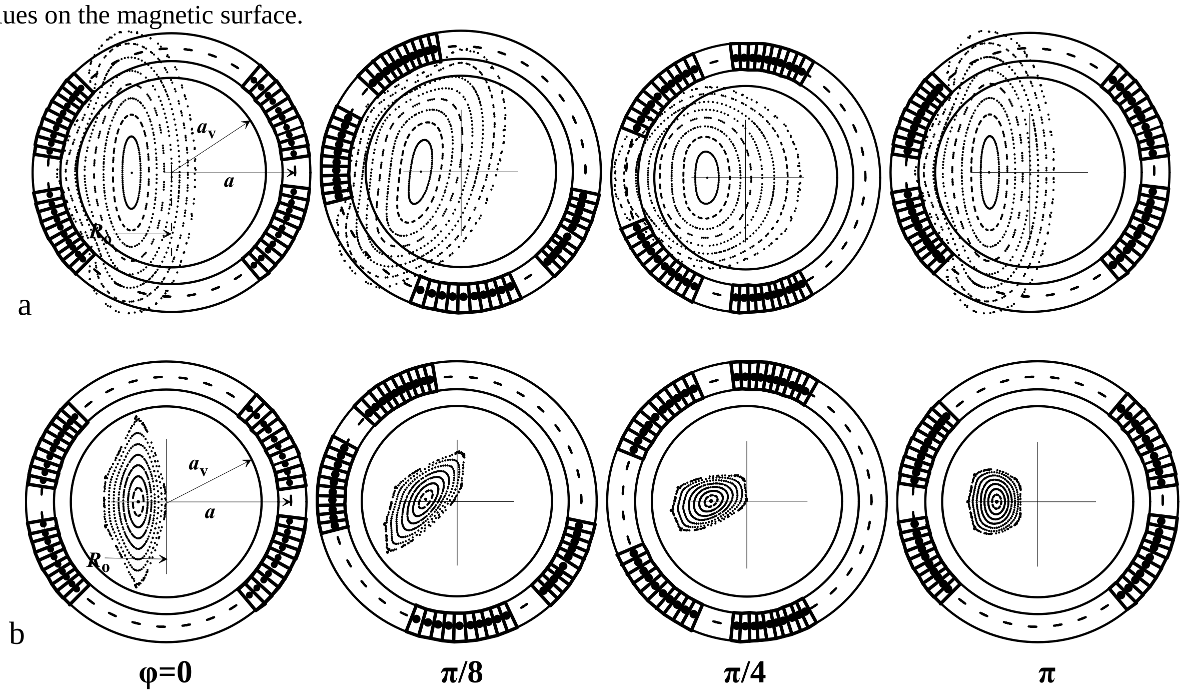

Fig. 2. Characteristic poloidal cross-sections (see Fig. 1) of the magnetic surface configuration in the base calculated model (a) and in the model by switching off two adjacent coils 1, 16 (b)

2.2. MIRROR-TYPE REGION

To estimate the longitudinal size of the mirror region the behavior of the magnetic axis characteristics along the two go-rounds over the length of the torus has been investigated (Fig. 3).

The top part of Fig. 3 represents the magnetic field value along the magnetic axis. One can see from the figure that the mirror region of the magnetic field appears between the switched off coils 1, 16. The mirror region longitudinal size can be limited by an interval $\Delta\varphi=\pi$ (0.65π) marked on the abscissa axis. The middle part of Fig. 3 shows that in the marked interval a maximal deformation of the magnetic axis trajectory along the major radius occurs, $\Delta(R_{ax}/R_0)$=0.027.

Magnetic axis trajectory deformation along the straight torus axis Z, i.e., the magnetic axis trajectory maximum deviation from equatorial torus plane in the marked interval (see the lower part of Fig. 3) is several lesser, $|Z_{ax}/R_0|\approx 0.005$.

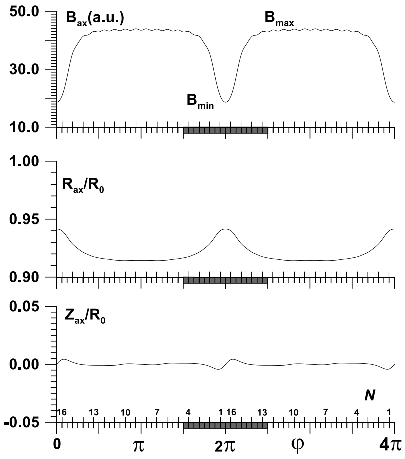

Fig. 3. The magnetic axis characteristics along two go-rounds over the length of the torus in combined magnetic system: B_{ax}(a.u.) – the magnetic field value; R_{ax}/R_0 – the projection of the magnetic axis major radius onto the equatorial torus plane; Z_{ax}/R_0 – magnetic axis deviation from equatorial torus plane

In case of switching off the other coil pair one can observe a magnetic axis trajectory displacement up or down relative to the equatorial plane. For example, the magnetic surface configuration, following the magnetic axis displacement $\Delta(Z/R_0) = 0.025(0.015)$, shifts downward by switching off the coils 16, 15. The upward displacement one can observe, for example, by switching off the coils 14, 13. With that there are not distinct changes in the magnetic surface parameters.

CONCLUSIONS

The numerical calculations have demonstrated the possibility of the closed magnetic surface existence in the combined magnetic system. The system contains the torsatron *U*-2M magnetic system model with the additional toroidal magnetic field coils and the mirror-type magnetic system model. The mirror-type magnetic system model is realized by switching off two adjacent coils of an additional toroidal magnetic field. The calculations carried out have shown that in comparison with switching off one coil the switching off two adjacent additional toroidal magnetic field coils in the *U*-2M torsatron device results in the mirror ratio value and the mirror region longitudinal size increase ~1.5 times as much.

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МАГНИТНЫЕ ПОВЕРХНОСТИ ТОРСАТРОНА У-2М С УВЕЛИЧЕННЫМ ПРОБОЧНЫМ ОТНОШЕНИЕМ

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Численными расчетами показано существование конфигурации замкнутых магнитных поверхностей с увеличенным пробочным отношением и большим продольным размером пробочной области в модели комбинированной магнитной системы. В состав модели входят магнитная система 2-заходного торсатрона У-2М с катушками дополнительного тороидального магнитного поля и магнитная система типа пробкотрон. Последняя реализуется путем отключения двух смежных катушек дополнительного тороидального магнитного поля.

МАГНІТНІ ПОВЕРХНІ ТОРСАТРОНА У-2М ЗІ ЗБІЛЬШЕНИМ ПРОБКОВИМ ВІДНОШЕННЯМ

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Чисельні розрахунки показали можливість існування конфігурації замкнутих магнітних поверхонь зі збільшеним пробковим відношенням і повздовжнім розміром пробкової області в моделі комбінованої магнітної системи. До складу моделі входять магнітна система 2-заходного торсатрона У-2М з котушками додаткового тороїдального магнітного поля та магнітна система типу пробкотрон. Остання реалізується шляхом відключення двох суміжних котушок додаткового тороїдального магнітного поля.