MAGNETIC FIELD OF HELIOTRON AND MIRROR-TYPE MAGNETIC SYSTEM COMBINATION

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In numerical calculations for the model of combined magnetic system a possibility of existence of closed magnetic surfaces is shown. The model comprises the magnetic system of *l*=2 torsatron without additional toroidal magnetic field coils (heliotron) with a single current-carrying turn as an element of the mirror-type magnetic system. The turn encircles the heliotron closed magnetic surface region and produces a magnetic field of opposite direction to the heliotron magnetic field.

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INTRODUCTION

As a fusion neutron source for the sub-critical fast hybrid reactor the magnetic plasma trap has been proposed on the basis of the combination of magnetic systems including a stellarator-type magnetic system and a conventional mirror-type system [1]. In numerical calculations for the combined magnetic system (CMS) model the study of a magnetic field has been carried out [2]. The model comprises a stellarator-type magnetic system of the *l*=2 torsatron with additional toroidal magnetic field coils with a single current-carrying turn as an element of the mirror magnetic system. The turn encircled the torsatron closed magnetic surface region and produced a magnetic field of unidirectional or opposite direction relative to the torsatron magnetic field. In the CMS model, taking into account the width of helical coils and that of additional toroidal magnetic field coils, the mirror-type magnetic system was realized by switching off one of the additional toroidal magnetic field coils [3].

In this paper the magnetic field of the CMS where the stellarator-type magnetic system is an *l*=2 torsatron without additional toroidal magnetic field coils, i.e. the model of a heliotron-type magnetic system is investigated. As is known [4], a similar magnetic system is in operation in the LHD heliotron magnetic plasma trap of steady-state action.

1. CALCULATION MODEL OF A HELIOTRON MAGNETIC SYSTEM

The calculation model of a heliotron magnetic system is schematically represented in Fig. 1. The main geometrical characteristics of the initial calculation model of the heliotron magnetic system are as follows:

– toroidicity $\alpha=a/R_0=0.25$, *a* is the minor radius of the torus, R_0 is the major radius of the torus;

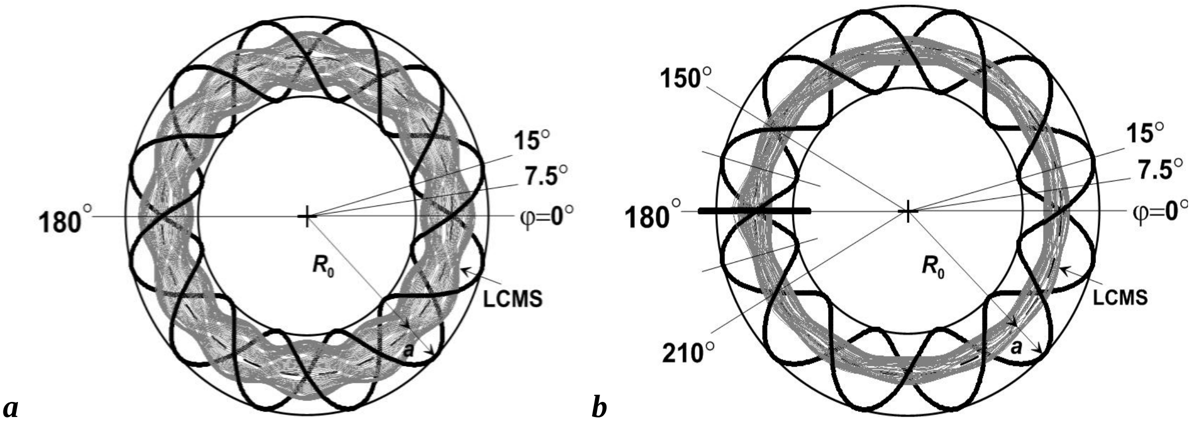
– *l*=2 is the polarity;

– *m*=6 is the number of helical coil pitches along the length of the torus, i.e., helical coil pitch parameter is $p=m\alpha=1.5$;

– each of the helical coils of the calculation model comprises one filament-like conductor;

– the helical coils are wound on the torus according to the cylindrical helix law, $\theta_1=m\varphi$, θ and φ denotes the poloidal angle and the toroidal angle consequently.

Fig. 1 also presents the projection of the last closed magnetic surface (LCMS), onto the equatorial torus plane. It is seen that the LCMS minor radius has a comparable value with the torus minor radius.



a ***b***

Fig. 1. Top view of the heliotron helical coils and the LCMS (a) and the CMS with the current-carrying turn (φ=180º) and the LCMS (b). The toroidal azimuths of poloidal cross-sections are indicated (see Fig. 2, 4)

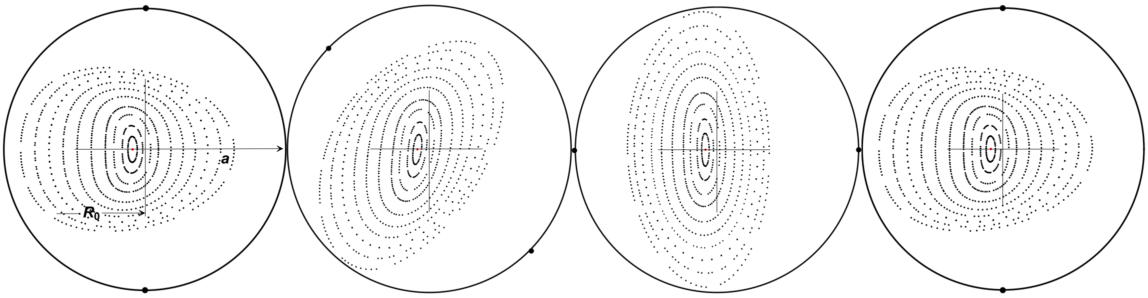


Fig. 2. Magnetic surface cross-sections in the initial heliotron

Fig. 2 shows the poloidal cross-sections of the magnetic surface configurations calculated for heliotron initial calculation model. The outer circle represents the torus cross-sections with traces of helical coils (large black points). The cross-sections are spaced apart by the toroidal angle φ (see Fig. 1) within the limits of the magnetic field half-period, φ=0º, 7.5º, 15º. The cross-section φ=180º at the assumed position of the turn is also presented. From the figure one can see that the size of the region of magnetic surface existence does not depend on the cross-section toroidal azimuth. In all the cross-sections the average radius of the last closed magnetic surface is the same, r_{1c}/R_0=0,18 (r_{1c}/a=0,72). The magnetic surface configuration shapes in the cross-sections φ=0º and φ=180º are identical.

It is also seen from Fig.2, that in all the cross sections the magnetic axis traces are disposed in the equatorial torus plane, its major radius R_{0ax}/R_0=0,978<1, i.e. the initial configuration of magnetic surfaces is in the mode with a planar magnetic axis and is shifted inward the torus. The mode can be realized with a uniform transverse compensating magnetic field B_z/B_0=0.25, where B_0 is the amplitude of the toroidal component of the magnetic field generated by helical coils on the circular axis of the torus. From Fig. 2 one can see, that magnetic surfaces are elongated along the vertical z-axis of the torus in the central part of the magnetic surface configuration. The magnetic surface ellipticity parameter is not lesser than 2 in the vicinity of the magnetic axis. So, on the analogy with present-day tokamaks, which have a noncircular D-shaped poloidal cross-section, in the central part of the plasma core of the heliotron under consideration one can expect the double increase in the limiting β-value.

The magnetic surface parameters as a function of their average radius r/R_0 are shown in Fig. 5 by dotted lines. From the figure it follows that the rotational transform angle (ι is in 2π units) increases with radius increasing ι=0.1→0.91, there is a magnetic hill U=0→0.23, and the mirror ratio $\gamma=B_{max}/B_{min}$=1.003→2.66. The parameter values for the last closed magnetic surface together with its average radius (in brackets) are indicated by lettering to the curves.

2. CALCULATION MODEL OF THE CMS

In the CMS under consideration the current-carrying turn takes place in the torus poloidal cross-section at the toroidal azimuth φ=180º (see Fig.1,b). The turn radius a_t/R_0=0.35, the turn center is on the circular axis of the torus The ratio of the turn current to the helical coil current is I_t/I_h=-0.36. Thus in the turn center the current produces a magnetic field B_{0t} in the opposite direction relative to the torsatron guiding magnetic field B_{0t}=-0.27B_0. Fig. 1,b presents the LCMS projection onto the equatorial torus plane. It is seen that superposition of the turn magnetic field diminishes the LCMS radius by a factor of ~2.

Fig. 3 represents the calculated poloidal cross sections of magnetic surfaces in the CMS. The average value of the last closed magnetic surface radius gradually increases from r_{1c}/R_0=0.09 in the cross-section φ=0º to r_{1c}/R_0=0.11 in the cross-section φ=180º.The island structure arises at the edge of the magnetic surface configuration. The magnetic axis looses the circle shape in the CMS. It is evidenced by the observed dependence of the magnetic axis trace position at the toroidal φ-azimuth of the poloidal cross-section. So, R_{ax}/R_o=0.983 in the φ=0º cross-section and R_{ax}/R_o=1.003 in φ=180º cross-section.

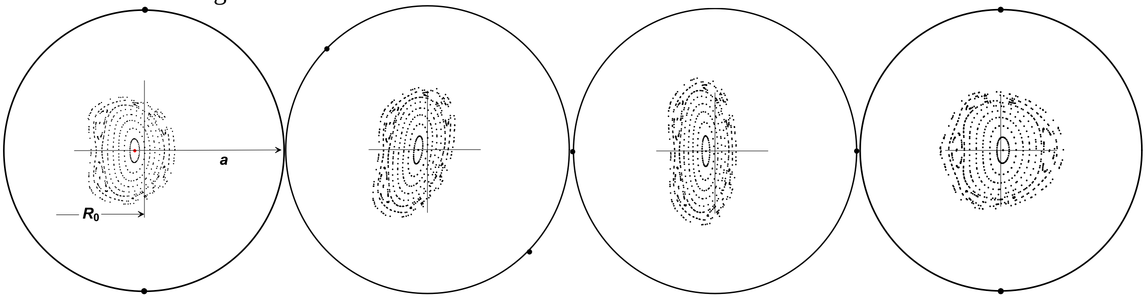


Fig. 3. Poloidal cross-sections of magnetic surfaces in the CMS

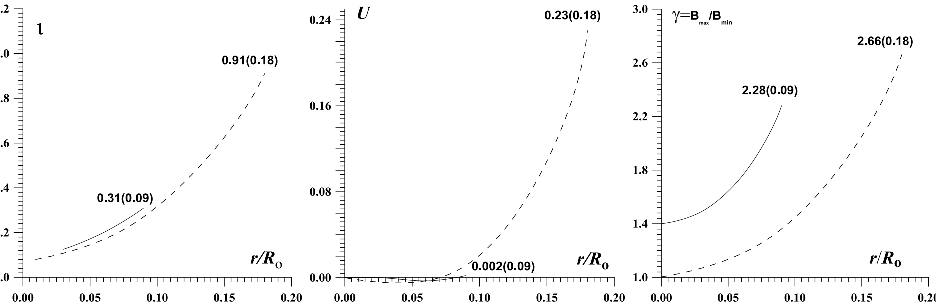


Fig. 4. Parameters of magnetic surfaces as a function of their average radius in the heliotron (dotted lines) and CMS (solid lines)

The radial dependences of the CMS magnetic surface parameters are shown in Fig. 4 by solid lines. It is seen from the figure that the value of the rotational transform angle changes (ι is in 2π units) within the limits $\iota_{axis}\rightarrow\iota_{lcms}$=0.12→0.31. The mirror ratio on the last closed magnetic surface is slightly decreased and that on the magnetic surfaces near by the magnetic axis is significantly increased as compared with the initial configuration γ=1,4→2.28. The high magnetic hill in the initial configuration is almost vanished, U=0.002.

3. MIRROR-TYPE REGION

The main aim of CMS is to create a mirror region with a decreased value of magnetic field strength in the heliotron field lines. The mirror region is formed in the vicinity of the turn. Below we shall estimate the longitudinal and transverse sizes of the mirror region and the "effective" value of the mirror ratio.

3.1. THE LONGITUDINAL SIZE OF THE MIRROR REGION

To estimate the longitudinal size of the mirror region the behaviour of the CMS magnetic axis characteristics has been investigated (see Fig.5). For comparison the magnetic axis characteristics of the initial heliotron are also presented in Fig. 5 by dotted lines.

The top part of Fig. 5 represents the magnetic field strength along the full length of the CMS magnetic axis. One can see from the figure that the mirror region of the magnetic field appears in the vicinity of the turn. Its longitudinal size can be limited by a short interval marked on the abscissa axis around the toroidal angle Δφ=150...210º. Within these interval the value of the mirror ratio $[\gamma_{ax}]$ on the CMS magnetic axis is $[\gamma_{ax}]$=0.95γ_{ax}=1.33. According to the designations in the figure $[\gamma_{ax}]=[B_{ax}]/[B_{ax}]_{min}$, and $\gamma_{ax}=B_{axmax}/[B_{ax}]_{min}$. The interval comprises two heliotron magnetic field periods, i.e., the mirror region half-length is L/R_0≈0.5. In the initial heliotron γ_{ax}=1.003 on the full magnetic axis length.

The middle part of Fig. 5 shows that the major radius of the CMS magnetic axis exceeds the magnetic axis major radius in the initial heliotron. The major radius of the CMS magnetic axis reaches the maximum value (R_{ax}/R_0=1.003) inside the interval at the turn toroidal azimuth.

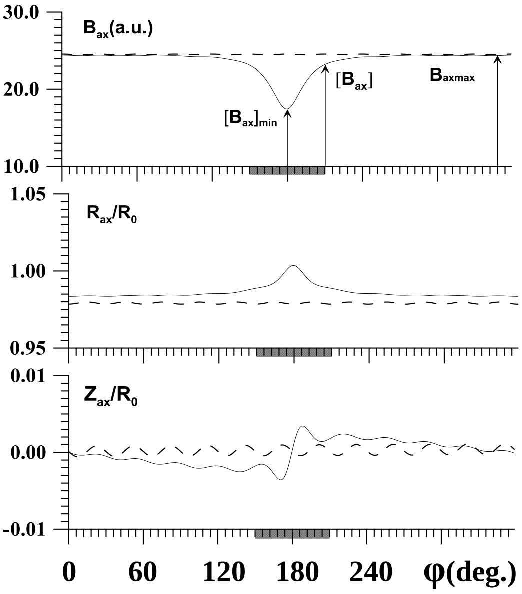
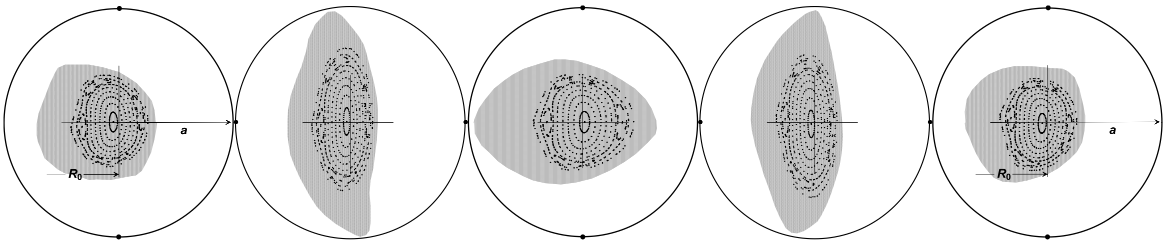


Fig. 5. Characteristics of the magnetic axis along its full length in the initial heliotron (dotted lines) and in the CMS (solid lines): B_{ax}(a.u.) − the magnetic field strength, R_{ax}/R_0 − the projection of the magnetic axis major radius onto the equatorial torus plane, Z_{ax}/R_0- magnetic axis deviation from equatorial torus plane

The lower part of Fig. 5 shows the CMS magnetic axis declination from the torus equatorial plane, Z_{ax}/R_0. The declination value gradually increases as oncoming to the turn azimuth, takes on the extreme values Z_{ax}/R_0=±0.003 inside the interval, and gets across zero at the turn azimuth. The initial heliotron magnetic axis declination is estimated by the accuracy of the calculation carrying out, $|Z_{ax}/R_0|$≈0.001.

3.2. TRANSVERSE SIZE OF THE MIRROR REGION

It is evident, that the mirror region comprises not only the sections of field lines forming regular magnetic surfaces, but the sections of field lines of destroyed magnetic surfaces at the periphery. Therefore the radial or cross size of the mirror region exceeds the LCMS cross size in all the poloidal cross sections of the torus. In the calculations the transverse mirror region size was determined under condition that the field line does not escape the torus surface in the interval Δφ=150…210°.



φ=210° **195°** **180°** **165°** **150°**

Fig. 6. Mirror region cross sections

Fig. 6 shows calculated cross sections of the mirror region (tinted). In the cross-sections with φ=150°, 210° at the interval ends the average radius of the mirror region boundary is r_{end}/R_0=0.13, inside the interval − r_{in}/R_0=0.17. Hence, according to the magnetic flow conservation law an "effective" value of the mirror ratio γ_{eff} within the mirror region boundary is equal to $\gamma_{eff}=(r_{in})^2/(r_{end})^2$=1.7. The "effective" value of the mirror ratio within the LCMS boundary has the intermediate value, γ_{lceff}=1.5.

CONCLUSIONS

In this study, the numerical calculations of the magnetic field produced by the model of a combined magnetic system were carried out. The model comprises a heliotron-type magnetic system with a single current-carrying turn as an element of the mirror-type magnetic system.The calculations show that the magnetic field produced by the current-carrying turn, being opposite to the heliotron magnetic field diminishes the region of existence of closed magnetic surfaces in the heliotron. In the place of the current-carrying turn a curvilinear mirror region appears. The region comprises the sections of magnetic surface field lines, as well as, the sections of field lines in the edge layer of destroyed magnetic surfaces. The curvilinear mirror region half-length exceeds its transverse maximum size ($2r_{in}/R_0$) by a factor of 1.5 (nonparaxial mirror trap), the average "effective" mirror ratio value is γ_{eff}=1.5.

Numerical calculations have been obtained using the idealized model regarded as heliotron and mirror-type magnetic systems. The next stage of investigations will evidently meet the necessity to determine the influence of finite size of CMS current-carrying coils.

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МАГНИТНОЕ ПОЛЕ КОМБИНАЦИИ МАГНИТНЫХ СИСТЕМ ГЕЛИОТРОНА И ПРОБКОТРОНА

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Численными расчётами показана возможность существования замкнутых магнитных поверхностей в модели комбинированной магнитной системы. В состав модели входят магнитная система 2-заходного торсатрона без катушек дополнительного тороидального магнитного поля (гелиотрон) и магнитная система пробкотрона в виде одиночного витка с током. Виток охватывает область существования замкнутых магнитных поверхностей гелиотрона и по отношению к магнитному полю гелиотрона создает магнитное поле встречного направления.

МАГНІТНЕ ПОЛЕ КОМБІНАЦІЇ МАГНІТНИХ СИСТЕМ ГЕЛІОТРОНА ТА ПРОБКОТРОНА

В.Г. Котенко

Чисельними розрахунками показана можливість існування замкнутих магнітних поверхонь у моделі комбінованої магнітної системи. До складу моделі належить магнітна система 2-заходного торсатрона без котушок додаткового тороїдального магнітного поля (геліотрон) та магнітна система пробкотрона у вигляді одного кільця зі струмом. Кільце охоплює область існування магнітних поверхонь геліотрона і створює по відношенню до магнітного поля геліотрона магнітне поле зустрічного напрямку.