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Magnetic field of heliotron with irregular helical coil pitch

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ABSTRACT

The paper presents the results of numerical calculations on the magnetic field of a heliotron with a helical coil pitch L_0, which comprises a helical coil section named as an L-section, where the helical coil pitch L differs from L_0, i.e. $L < L_0$. The calculations have shown that within the L-section the real preconditions exist permitting to form both the plasma core of passing plasma particles and of the SOL plasma boundary being at the increased distance from the wall in the high magnetic field region.

1. Introduction

In the existing stellarator-type magnetic systems with helical coils the helical coil pitch length L_0 is constant [1]. In this paper we have applied numerical calculations to investigate the magnetic field properties of heliotron with an irregular helical coil pitch. The heliotron helical coil with a pitch L_0 comprises an L-section, where the helical coil pitch L differs from L_0, i.e. $L \neq L_0$. Here the L-section with increased magnetic field ($L < L_0$) is investigated.

The purpose of the study is to estimate a possibility of the heliotron magnetic system new modification for applications in the controlled fusion researches. It is not impossible that the magnetic system can be applied for increasing the plasma-wall spacing in the fusion reactor [2] and for making a restricted fusion reactor "hot zone" as long as L-section length is. Probably, between two small-scale L-sections a region of stellarator-type and mirror-type magnetic field superposition [3] can be generated.

2. Calculation model of the base heliotron magnetic system

The calculation model of the base heliotron magnetic system is schematically represented in Fig. 1. The main geometry features of the calculation model of the base heliotron magnetic system are as follows [4]:

- the toroidicity $a/R_0 = 0.25$, where a is the minor radius of the torus, R_0 is the major radius of the torus;
- the helical coil polarity $l = 2$;
- the number of helical coil pitches $m = 6$. The test numerical calculations have shown that the region of closed magnetic surface existence extends with m increasing. However, in the real $l = 2$ heliotron with $m > 6$ the difficulties can appear with access to the working volume and the rotational transformation angle value;
- each of the helical coils in the calculation model comprises one filament-like conductor;
- the helical coils are wound on the torus according to the cylindrical helix law, $\theta = m\varphi$, θ and φ denotes the poloidal angle and the toroidal angle (azimuth) consequently.

Fig. 2 shows the poloidal cross-sections of the magnetic surface configuration calculated for the model of the base heliotron. 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, $\varphi = 0°, 7.5°, 15°$. The cross-section $\varphi = 180°$ is presented too.

The figure shows that the size of the region of closed magnetic surface existence does not depend on the cross-section toroidal azimuth. In all the cross-sections the average radius r_{lc} of the last closed magnetic surface (LCMS) is the same, $r_{lc}/R_0 = 0.18$ ($r_{lc}/a = 0.72$). The shape of the magnetic surface configuration in the cross-sections $\varphi = 0°$ and $\varphi = 180°$ is the same.

It is also seen from Fig. 2, that the magnetic surface configuration is well centered. In all the cross sections the magnetic axis traces take place in equatorial plane of the torus, the magnetic axis major radius is $R_{0ax}/R_0 \approx 1.003$. This mode can be realized with a uniform transverse compensating magnetic field $B_z/B_0 = 0.241$, where B_0 is the amplitude of the toroidal component of the magnetic field generated by the helical coils on the circular torus axis. In all the subsequent calculations the value of this ratio is invariable.

The magnetic surface parameters as a function of their average radius r/R_0 are presented in Fig. 5 by dashed lines. The rotational transformation angle (ι is in 2π units) increases with the average radius increasing ($\iota = 0.07 \rightarrow 0.92$), there is a small magnetic well $U = -0.015$ in the centre of the magnetic surface configuration and a magnetic hill

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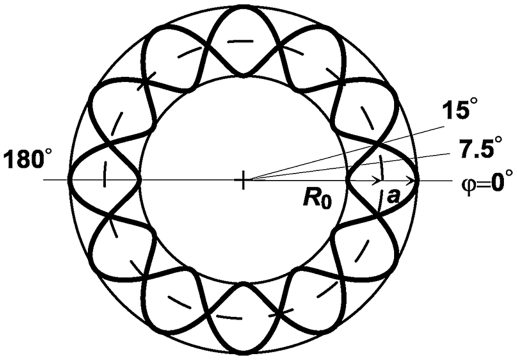


Fig. 1. Top view of the l = 2, m = 6 base heliotron magnetic system. The toroidal azimuths of poloidal cross-sections are indicated.

U = 0.16 at the configuration edge. The maximum mirror ratio on the magnetic surfaces $\gamma = B_{\max}/B_{\min}$ = 1.003→2.65, where $B_{\max}$, $B_{\min}$ denote the maximum and minimum magnetic field strength, respectively.

3. l = 2, m = 6 Heliotron with helical coil *L*-section

Here we will clear out an influence of helical coil L-section on the magnetic surfaces of the base heliotron. The calculation model of the l = 2, m = 6 heliotron with helical coil L-section is schematically shown in Fig. 3. As well as in the base heliotron a major part of helical coil (pos.1) is wounded on the torus by $\theta = m\varphi$ law with a helical coil pitch $L_0 = 2\pi R_0/m$.

For the ~k times magnetic field increase ($k > 1$) within the L-section, the L-section helical coils (pos.2) are wounded on the torus by the $\theta = km\varphi$ law with a helical coil pitch $L_0 = 2\pi R_0/km$. In the paper the k = 3 case is under consideration, i.e., the L-section helical coil pitch is $L = L_0/3 = 2\pi R_0/3m$.

To avoid a very large damage of the magnetic surface configuration the base and L-section helical coils should be joined in the points where the smooth mutual transition between the coils is possible. The smooth transition of the base helical coil $\theta = 6\varphi$ into the L-section helical coil $\theta = 18\varphi$ is realized on the toroidal azimuths $\varphi = 165°$ and $\varphi = 195°$, the minimal length of L-section is $L_0/2$ (see Appendix A). The L-section geometrical center is on the toroidal azimuth $\varphi = 180°$. To provide the conversion smoothness in the magnetic field calculations, carried out by the Biot-Savart law, the condition $\Delta L \sim 10^{-2}L$ has been fulfilled (ΔL is the elementary helical coil segment with helical coil current).

Fig. 4 shows the poloidal cross-sections of the magnetic surface configuration calculated for the heliotron model with the L-section. Principal distinction between the calculated magnetic surface configuration and the base configuration is that the poloidal cross-section area of the calculated configuration decreases, as it comes nearer to the L-section.The maximum area cross-section $S_{\max}$ is on the azimuth $\varphi = 0°$, where the LCMS average radius is 1.6 times less than the LCMS average radius in the base heliotron, $r_{lc}/R_0 = 0.11$. The minimum area cross-section $S_{\min}$ is found on the azimuth $\varphi = 180°$ in the middle of the helical coil L-section, where the LCMS average radius is $r_{lc}/R_0 = 0.065$.

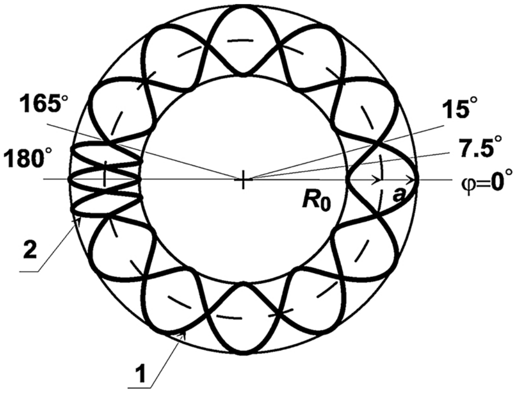


Fig. 3. Top view of the l = 2, m = 6 heliotron with helical coil L-section: 1- helical coils with pitch L_0, 2- L-section helical coils with pitch $L = L_0/3$.

The ratio $S_{\max}/S_{\min} \sim 3$ is the value of the pinch ratio of the magnetic surface configuration.

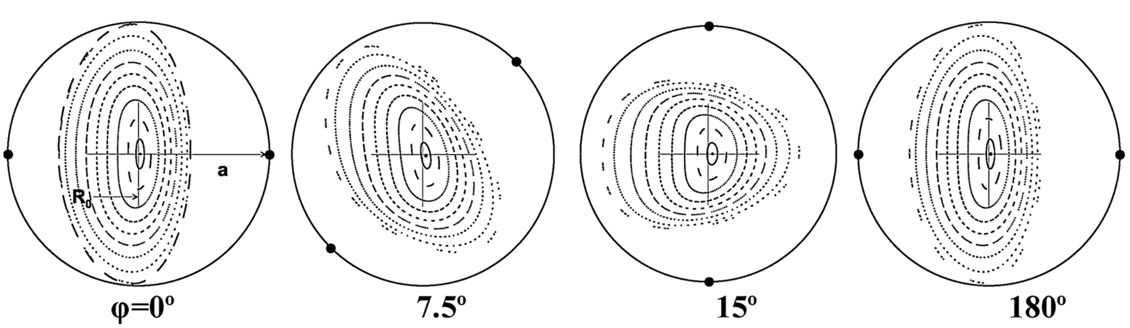
The magnetic surface poloidal cross-section decrease is accompanied by the gradual decrease of magnetic axis major radius R_{ax}/R_0, i.e. by the magnetic surface configuration shift into the torus. The magnetic axis major radius is $R_{ax}/R_0 = 1.008$ for $\varphi = 0°$ and $R_{ax}/R_0 = 0.981$ for $\varphi = 180°$.

The dashed lines in Fig. 4 in the poloidal cross-sections of $\varphi = 0°$ and $\varphi = 180°$ show the cross-sections of the outer boundary of the stochastic field line layer [5,6], i.e. the boundary of the plasma layer having the transient plasma parameters (SOL plasma). It is seen that in the cross-sections of $\varphi = 180°$ the stochastic field line layer boundary is at increased distance from the torus surface. In the base heliotron the stochastic field line layer boundary is very close to the LCMS poloidal cross-section contour. In real heliotron with a finite-size helical coil cross-section a significant helical divertor slit narrowing will take place within L-section that can affect adversely on helical divertor efficiency. It is very likely that the problem can be settled with application of specific divertor design conceptions [7,8].

The magnetic surface parameters as a function of their average radius in the cross-section of $\varphi = 0°$ are shown in Fig. 5 by solid lines. The parameter values for the last closed magnetic surface together with its average radius (in brackets) are indicated near the curves. It is seen from the figure that the magnetic surface parameters (ι and U) are comparable with the magnetic surface parameters of the base heliotron for $r/R_0 < 0.11$.

The maximum value of the mirror ratio γ on the magnetic surfaces undergoes a drastic change. It follows from the figure that the γ-value is in the range of $2.5 < \gamma < 3.5$. The result is rather evident because with the same current value in the L-section the helical coil winding density is three times more, then in the base helical coil part.

The idea of the value and the shape of the magnetic field ripple $B_{\max}$ in the l = 2, m = 6 heliotron with the L-section one can see at consideration of Fig. 6. The L-section position is marked on the abscissa axis by the bold segment in the figure.



φ=0° 7.5° 15° 180°

Fig. 2. Magnetic surface cross-sections in the base l = 2, m = 6 heliotron.