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HELIOTRON MAGNETIC SYSTEM OF A FUSION NEUTRON SOURCE

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Numerical calculations have been carried out on magnetic field of heliotron magnetic system with a region of stellarator and mirror-type magnetic field superposition. Formation of a region of magnetic field superposition takes place in the gap between two helical coil sections which have reduced pitch length L in comparison with pitch length L_0 of the heliotron helical coils, $L=L_0/3$.

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INTRODUCTION

Based on numerical calculations in paper [1], it has been found that the closed magnetic surface configuration can exist in the heliotron magnetic system, the helical coil of which comprises an L-section, where a helical coil pitch L is less then the base helical coil pitch L_0. Subsequently in paper [2] it has been shown that in the gap between the two L-sections there can be formed a region of stellarator and mirror-type magnetic field superposition. It is supposed [3] that in the superposition region there is a possibility of creating the conditions for high-temperature D-T plasma confinement in the fusion neutron source [4, 5].

The calculations [1, 2] were based on an idealized calculation model of the heliotron magnetic system with thin helical coils. The compensation of the vertical magnetic field, generated by the toroidal unipolar helical currents, was carried out, in these calculations, by superposition of a perfectly homogeneous vertical magnetic field of the corresponding value and direction [6].

The presented paper reports the results of numerical calculations on the magnetic field of heliotron magnetic system model forming a region of stellarator and mirror-type magnetic field superposition considering a possible helical coil width and practical vertical magnetic field compensation circuit.

1. CALCULATION MODEL

The initial magnetic system model is a base idealized calculation model of the l=2, m=6 heliotron magnetic system [1, 2]:

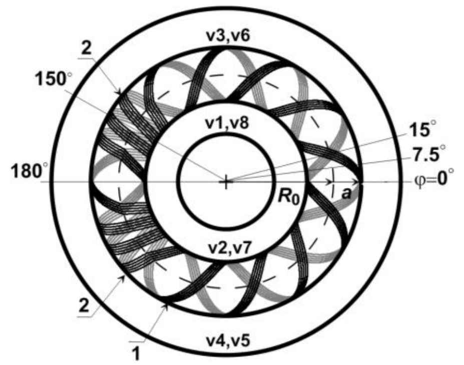
– toroidicity a/R_0=0.25, R_0 is the major torus radius, a is the minor torus radius (the helical coil average radius, the helical coil radial thickness is not considered in the calculations);

– number of helical coils l=2 (polarity);

– number of helical coil pitches m=6 along the torus length, $L_0=2\pi R_0/m$ is the pitch length;

– each helical coil is wound on the torus according to the cylindrical law $\theta(\varphi)=m\varphi$, where φ is the toroidal angle and θ is the poloidal angle.

The schematic diagram of the calculation model of the l=2, m=6 heliotron magnetic system with the two helical coil L-sections forming a region of stellarator and mirror-type magnetic field superposition is shown in Figs. 1,a, b.



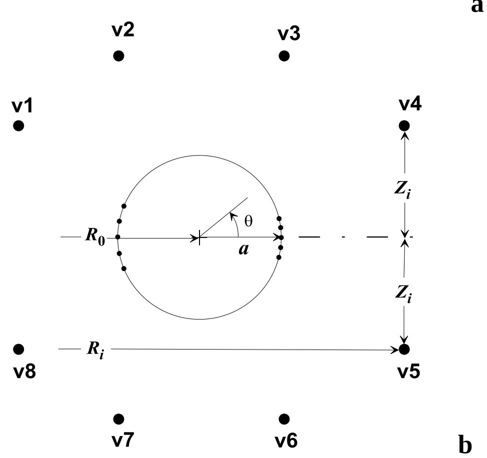


Fig. 1. Magnetic system of the l=2, m=6 heliotron with helical coil pitch L_0 (1) and two L-sections (2) with helical coil pitch L and compensation coil system (v1-v8): a – top view, b – poloidal cross-section φ=0°

It is seen from the figure that the helical coil of the calculation model has a finite width, which is approximated with a set of N=5 thin helical conductors. The central helical coil conductor is wound on the torus according to the law $\theta=m\varphi$ of the base model. The rest of the helical coil conductors are arranged turn-by-turn symmetrically on the both sides of the central conductor [7]. A smooth transition of the base helical coil into the two helical coil L-sections, which are wound on the torus according to the law $\theta=3m\varphi$, is realized on the toroidal azimuths φ=135º (165º) and φ=195º (225º).

The *L*-sections are located symmetrically relative to the toroidal azimuth φ=180°, the length of *L*-sections is $L_0/2$, the distance between them, in the case shown in Fig. 1, is $L_0/2$ too. The region of stellarator and mirror-type magnetic field superposition takes place in the gap between the *L*-section central cross-sections (φ=150º and φ=210º). The longitudinal length of the region, L_0, was measured along the torus circular axis. A total number of the conductor helical coil turns (current I_h) $W_h=N(W_{L0}+W_L)=80$, here $W_{L0}=10$ is the number of the base helical coil pitch L_0, $W_L=6$ is the number of helical coil pitch $L=L_0/3$ in the *L*-sections.

To compensate the vertical magnetic field of the heliotron model we applied a practical compensation circuit developed for the *l*=2, *m*=2 torsatron U-2M [8]. Fig. 1,a,b shows that the circuit is composed of 4 pairs of ring-shaped compensating coils. In each pair the coils, of major radius R_i, are symmetric relative to the equatorial torus plane (Z=0) at the distance Z_i from it. Each ring-shaped coil consists of 5 conductor turns. Total number of the ring-shaped coil conductor turns $W_v=40$ (current I_v). The compensating circuit application in the calculations of the *l*=2, *m*=6 heliotron magnetic system model was succeeded earlier [9].

Also the circuit comprises 4 auxiliary ring-shaped correction coils. They are designed for fine tuning of the compensating magnetic field radial distribution. The correction coil radii are very close to the radii R_i of the compensation coils v1, v4, v5, v8 which are arranged like the compensation coil pairs v1-v8 and v4-v5, respectively. Each correction coil comprises 8 conductor turns. Total number of the correction conductor turns $W_c=32$ (current I_c).

2. RESULTS OF CALCULATIONS

The purpose of calculations is to estimate the parameters of stellarator and mirror-type components of the superposition region magnetic fields.

2.1. MAGNETIC SURFACE CONFIGURATION

Fig. 2 represents the poloidal cross-sections of the magnetic surface configuration calculated for the *l*=2, *m*=6 heliotron with two *L*-sections. The configuration is realized due to the compensation of the helical coil vertical magnetic field by the vertical magnetic field of opposite direction. This field is produced by the ring-shaped compensation coils due to the ratio value $I_vW_v/I_hW_h=0.1952$, where I_vW_v is the total ampere-turns of the series ring-shaped compensation coils, I_hW_h is the total ampere-turns of the series helical coils. There was no a vertical magnetic field correction in the calculation ($I_cW_c=0$).

It follows from Fig. 2 that the poloidal cross-section area of the magnetic surface configuration depends on the toroidal azimuth φ. The maximum area cross-section is located on the azimuth φ=0°, where the last closed magnetic surface (LCMS) average radius is $r_{lc0}/R_0=0.083$. The minimum area cross-section is found on the azimuth φ=150° (210°) in the middle of the *L*-sections, where LCMS average radius is $r_{lc150}/R_0=r_{lc210}/R_0=0.06$. Within the magnetic field superposition region the maximum area cross-section is found on the azimuth φ=180°, where LCMS average radius is $r_{lc180}/R_0=0.078$.

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 magnetic surface configuration shift into the torus. The magnetic axis major radius is $R_{ax}/R_0=1$ for φ=0°. Within the magnetic field superposition region R_{ax} is some percent below R_0: $R_{ax150}/R_0=R_{ax210}/R_0=0.973$, $R_{ax180}/R_0=0.980$. So, the longitudinal length of the magnetic field superposition region measured along the magnetic axis is closely approximated to the length L_0, measured along the torus circular axis.

The dashed lines in Fig. 2 in the poloidal cross-sections of φ=0, 150 and 180° show the cross-sections of the outer boundary of the stochastic field line layer [10, 11], i.e. the boundary of the plasma layer having the transient plasma parameters (SOL plasma). It is seen that in the cross-sections φ=150 and 180° the stochastic field line layer boundary is at some distance from the torus surface.

The magnetic surface parameters as a function of their average radius in the cross-section of φ=0° are shown in Fig. 3. It follows from the figure that there are, on the magnetic surfaces of heliotron with magnetic field superposition region, a rotational transformation angle ι=0.1→0.15 (in 2π units) and a magnetic well *U*=-0.065. The maximum mirror ratio $\gamma=B_{max}/B_{min}$= 2.5→3.6, where B_{max}, B_{min} denote the maximum and minimum magnetic field strength on the magnetic surfaces.

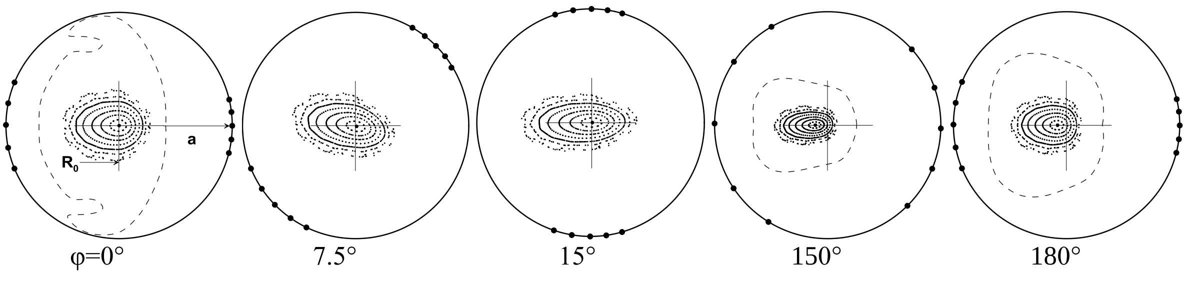


Fig. 2. Cross-sections of the magnetic surface configuration in the l=2, m=6 heliotron with magnetic field superposition region. In the cross-sections φ=0, 150, 180° the surfaces of the outer boundary of the stochastic field line layer (dashed lines) are also shown

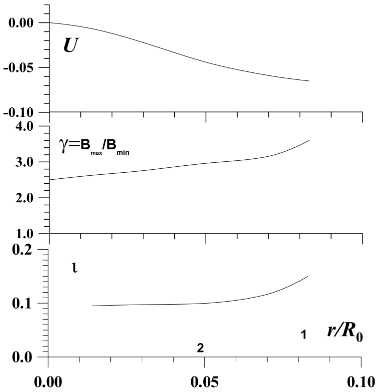


Fig. 3. Parameters of the magnetic surfaces as a function of their average radius in the φ=0° cross-section in the l=2, m=6 heliotron with the magnetic field superposition region

2.2. MIRROR-TYPE COMPONENT PARAMETERS

The calculations enable us to estimate two parameters which characterize the mirror-type component of the magnetic field superposition region. These include a ratio of the longitudinal length of the magnetic field superposition region (the full distance between mirrors) to the diameter of the maximum cross-section region (in a half distance between mirrors) and the maximum effective mirror ratio.

It was stated above that the length of the magnetic field superposition region coincides within a few percent with the base helical coil pitch length L_0 (1.05 in R_0 units). The radial boundary of the magnetic field superposition region should be regarded as an outer boundary of the stochastic field line layer because the region comprises not only regular magnetic surface field line sections, but the sections of field lines of the peripheral destroyed magnetic surface layer. The maximum average radius of the outer boundary of the stochastic layer in the superposition region is r_{180}/R_0=0.15 in the cross-section φ=180°, and the minimum average radius of the region in the cross-section φ=150° is r_{150}/R_0=0.11. Consequently, the magnetic field superposition region length is ~3 times more than the maximum diameter of the outer boundary of the stochastic field line layer within the region. According to the law of conservation of magnetic flow the effective value of the mirror ratio in the superposition region is $\gamma_{eff}=(r_{180})^2/(r_{150})^2=1.86$.

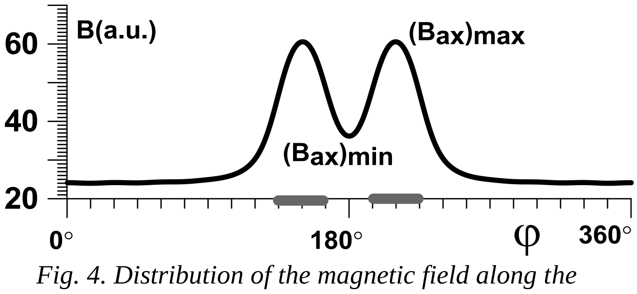


Fig. 4. Distribution of the magnetic field along the magnetic axis in the l=2, m=6 heliotron with the magnetic field superposition region

Fig. 4 represents the shape and value of the magnetic field ripples on the magnetic axis of the magnetic surface configuration. The *L*-section positions are marked on the abscissa axis by the bold segments. On the magnetic axis in the magnetic field superposition region the maximum value of the mirror ratio is $(B_{ax})_{max}/(B_{ax})_{min}$=1.7.

CONCLUSIONS

The calculation results indicate the possibility of creating the region of stellarator and mirror-type magnetic field superposition in the *l*=2, *m*=6 heliotron with two helical coil *L*-sections. In terms of forming the background plasma, incoming into the magnetic field superposition region, the closed magnetic surface configuration parameters can be considered satisfactory. The length of the magnetic field superposition region (the full distance between the mirrors) in relation to its maximum diameter (in a half distance between mirrors) is found in the range relevant to the non-paraxial mirror machines just as the maximum effective mirror ratio value [12].

Under the heliotron magnetic system curvature the magnetic field superposition region sustains a significant deviation from the straightness that is a classic mirror machine characteristic feature. The deviation effect on the high-temperature D-T plasma confinement in the magnetic field superposition region can be studied experimentally using the presented *l*=2, *m*=6 heliotron with two helical coil *L*-sections. In such a case to create a stellarator-type and mirror-type magnetic field superposition region there is no need for the members of the mirror coils and their power supply in addition to the heliotron magnetic system construction.

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МАГНИТНАЯ СИСТЕМА ИСТОЧНИКА ТЕРМОЯДЕРНЫХ НЕЙТРОНОВ НА ОСНОВЕ ГЕЛИОТРОНА

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Проведены численные расчеты магнитного поля магнитной системы гелиотрона с областью совмещения магнитных полей стеллараторного и пробкотронного типов. Формирование области совмещения магнитных полей осуществляется в зазоре между двумя участками винтовой обмотки с уменьшенной длиной шага L по сравнению с длиной основного шага L_0 винтовой обмотки гелиотрона, $L=L_0/3$.

МАГНІТНА СИСТЕМА ДЖЕРЕЛА ТЕРМОЯДЕРНИХ НЕЙТРОНІВ НА ОСНОВІ ГЕЛІОТРОНА

В.Г. Котенко, В.Є. Моісеєнко

Проведені чисельні розрахунки магнітного поля геліотрона з областю суміщення магнітних полів стелараторного та пробкотронного типів. Формування області суміщення магнітних полів здійснюється в проміжку між двома ділянками гвинтової обмотки зі зменшеною довжиною L кроку в порівнянні з довжиною основного кроку L_0 гвинтової обмотки, $L=L_0/3$.