THE l=2 STELLARATOR WITH DISPLACED HELICAL WINDINGS

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The paper deals with the magnetic surface configuration properties in the frame of a new model of the l=2 stellarator with displaced helical windings. The displacement has been made to provide a better access to the plasma confinement volume. Numerical calculations have shown that the magnetic surface configuration, shifted inward the torus and appearing favorable for plasma confinement, can be realized in the absence of a transverse magnetic field.
PACS: 52.55.Hc

INTRODUCTION

For effective use of means for plasma production, heating and diagnostics the plasma trap design must provide good access to the plasma confinement volume. In stellarator-type closed magnetic systems the toroidal field B_o coils and the helical windings restrict the access. In particular, the l=2 classical stellarator structure has 4 helical windings with alternating directions of current. The helical windings are uniformly distributed in the poloidal angle θ, and the average angle gap between the neighboring helical windings does not exceed $\Delta\theta \sim \pi/2$. The l=2 torsatron structure has 2 helical windings (with unidirectional current). Therefore, for the same area of the torus surface free of helical windings, the gap between the helical windings in the torsatron is nearly two times greater than that in the stellarator.

However, the unidirectional helical currents give rise to a high transverse (perpendicular to the equatorial plane of the torus) magnetic field in the torsatron. Its compensation is the necessary condition to form the plasma confinement region (closed magnetic surfaces) in the torsatron. To keep the access to the plasma confinement volume up to the mark, the compensation is performed with a limited number of compensating coils (2-6) and is usually not ideal. So, in a real torsatron device there is always a portion of uncompensated transverse magnetic flux. Some variations in the magnetic flux value, caused, for example, by the magnetic system power source instability, will induce the toroidal loop voltage. As a result, the production of plasma free of both the Ohmic current and the runaway electron current in the torsatron presents some difficulties. The classical stellarator having alternate-direction helical currents on the torus surface does not suffer from this disadvantage in principle. Moreover, the stellarator magnetic system has obvious advantages that stem from the possibility of varying independently the helical and longitudinal magnetic field amplitudes, and also from a low level of magnetic leakage field.

This report presents some recent numerical calculations for a new model of the l=2 stellarator magnetic system with displaced helical windings. The displacement is done in such a manner that 2 opposite angle gaps become greater ($\Delta\theta > \pi/2$) by one and the same value, and 2 other gaps are reduced ($\Delta\theta = \delta < \pi/2$) by the same value. The displacement is carried out to make the access to the plasma confinement volume in the l=2 stellarator as convenient as in the case of the l=2 torsatron.

LINEAR CONFIGURATION

Originally, the magnetic field structure in the helical system can be inferred, as usual, from the consideration of the linear approximation. In this case, the magnetic field has the helical symmetry and can be described analytically [1]. If $\varepsilon = 2\pi a/L \ll 1$ (a is the radius of the cylinder carrying the helical currents I, L is the pitch length of the helical winding), then one can determine the magnetic surface function $\Psi(r, \theta)$ in the straight helical magnetic system presented in Fig.1.

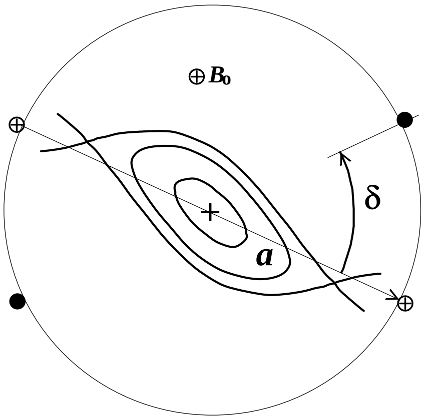


Fig.1. Cross-section of the straight l=2 stellarator with displaced helical windings: δ is the minor gap between the helical windings. The magnetic field B_o coils are not shown

The magnetic surface function has the form:

$$\Psi(r,\theta) = B_o \varepsilon \frac{(r/a)^2}{2} - \\ -\frac{\mu_o I}{2\pi} \ln \frac{1 - 2(r/a)^2 \cos 2(\theta - 2\pi\zeta/L - \delta/2) + (r/a)^4}{1 - 2(r/a)^2 \cos 2(\theta - 2\pi\zeta/L + \delta/2) + (r/a)^4}, \quad (1)$$

here r, θ, ζ are the cylindrical coordinates, μ_o is the magnetic constant.

Fig.1 also shows the magnetic surfaces cross-sections calculated by eq. (1) at a minor gap value $\delta = 50^o$. It can be seen, that the magnetic axis of the magnetic surface configuration is coincident with the axis of the cylinder, similarly to the l=2 classical stellarator ($\delta = 90^o$). The distinctive feature of this configuration is a complicated position of the separatrix ribs, difficult to describe analytically.

Problems of Atomic Science and Technology. 2007, № 1. Series: Plasma Physics (13), p. 18-20

CALCULATION MODEL

Numerical calculations of the toroidal model of *l*=2 stellarator with displaced helical windings were carried out using the basic parameters of *l*=2 torsatron *U*-2M [2]. It is known that the torsatron *U*-2M magnetic system contains toroidal magnetic field B_o coils, and either of the two helical windings of the torsatron *U*-2M consists of two equal parts. The parts are spaced by a diagnostic gap (see Fig.2) and are provided with individual current feeds. These technical peculiarities make it possible to turn on the parts in accordance with the *l*=2 stellarator scheme.

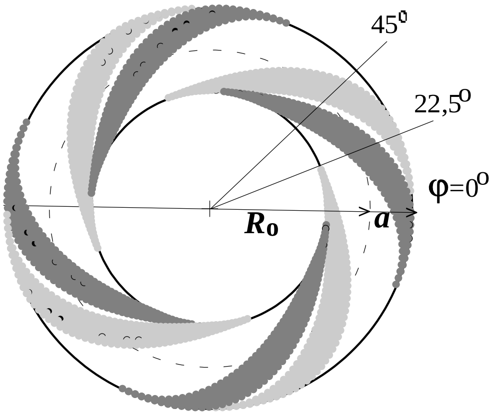


Fig.2. Top view of helical windings of the l=2 stellarator calculation model. One can see the small diagnostic gap and the large gap between the helical windings with alternate-direction current. The toroidal azimuths of poloidal cross-sections are shown (see Fig.3)

So, the 4 parts of the torsatron helical windings with unidirectional current turn into 4 displaced stellarator helical windings with alternate direction of the current. This provides the possibility to compare the magnetic surface parameters in both the *l*=2 stellarator and the *l*=2 torsatron, the value of the large gap between the helical windings being the same.

The parameters of the calculation model were the following:

-toroidicity a/R_o=0.2618, *a* is the minor radius of the torus, R_o is the major radius;

-the number of helical pitches of the helical winding along the torus *m*=2;

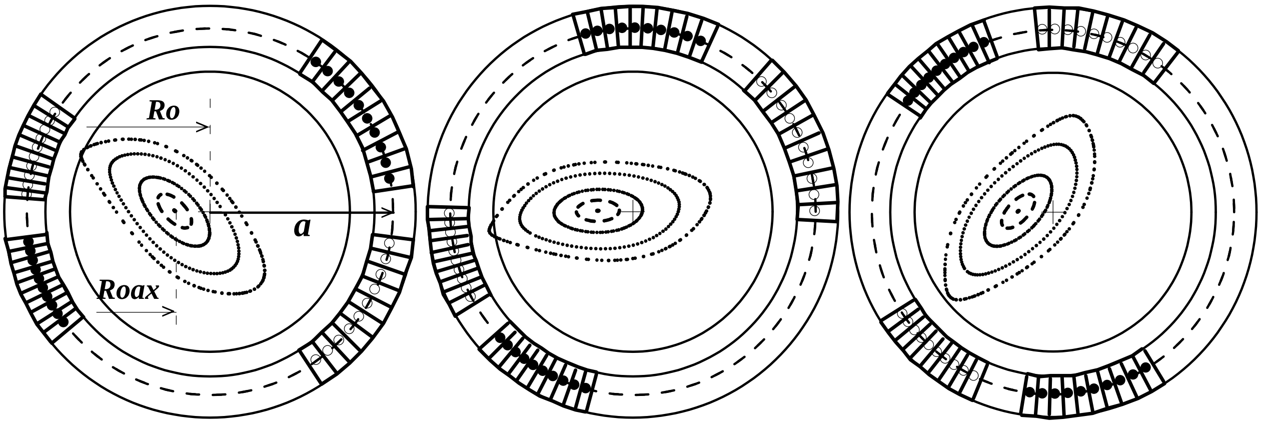
-the number of conductor turns in each of the 4 parts of the helical windings is 10;

-the model *U*-2M version [3-5] has been considered, where each of 40 helical conductors is wound round the torus by the same winding law (equi-inclination law $\theta(\varphi)=2\mathrm{arctg}(1.3074\mathrm{tg}\varphi)$, φ is the toroidal angle, θ is the poloidal angle);

-the average value of minor gap between the middle of the helical windings is $\delta\sim50^o$, the large gap value is ~130°. The system is plunged into an axisymmetric toroidal magnetic field $B_\varphi=B_oR_o/R$, B_o is the toroidal magnetic field value on the circular axis of the torus, *R* is the radial position of the observation point reckoned from the straight axis *z* of the torus. At basic operating conditions, the transverse magnetic field is B_z=0.

RESULTS OF CALCULATIONS

Figure 3 shows the calculated poloidal cross-sections of magnetic surfaces in the *l*=2 stellarator with displaced helical windings. The cross-sections are spased apart in the toroidal angle φ within the halfperiod of the magnetic field, φ=0°, 22.5°,45° (see Fig. 2). The inner circle represents the cross-section of the torsatron *U*-2M vacuum chamber. The present results of calculations refer to the magnetic surface configuration with the last closed magnetic surface (LCMS) falling into the vacuum chamber size. The trapezoidal figures depict the contours of helical-conductor cross-sections. The dots and circles inside the figures show the positions of thin current-carrying conductors with the alternate directions of the currents. They are located on the torus surface a/R_o=0.2618 (dashed circle). It is seen from Fig. 3 that the magnetic-axis trace belongs to the equatorial plain of the torus. The planar magnetic-axis major radius is R_{oax}/R_o=0.951. Since R_{oax}/R_o <1, the magnetic surface configuration appears shifted inward the torus. The shifted inward the torus configuration with a planar magnetic axis is the most attractive from the viewpoint of plasma confinement in torsatrons [6-8]. The configuration is realized at zero value of the transverse magnetic field, B_z=0. The magnetic surface parameters are practically coincident with magnetic surface parameters of the initial *U*-2M model version in the regime with a planar magnetic axis [5].



φ=0° φ=22.5° φ=45°

Fig.3. The cross-sections of magnetic surface configuration in the l=2 stellarator with displaced helical windings

The rotational transform angle increases with an increasing average magnetic-surface radius r, ι=0.42→0.63 (ι unit measure is 2π). The configuration shows a magnetic hill, U=0→0.056. The calculated magnetic field ripples on the magnetic surfaces are close to the minimal value $\gamma_{min}\approx(R_{oax}+r)/(R_{oax}-r)$, γ=1.008→1.38. In comparison with the l=2 torsatron model, the position of the planar magnetic axis and the average radius of the LCMS r_{lc}, $r_{lc}/R_o\approx0.1$ also remain unchanged.

To make the date complete, numerical calculations of an analogous model of the l=2 classical stellarator (δ=90°) were carried out. They give two main magnetic-surface parameters to be quite different: ι=0.7→1.05, U=0→0.01.

CONCLUSIONS

A new model of l=2 stellarator–type magnetic system with displaced helical windings has been discussed. The model provides a better access to the plasma confinement volume.

The magnetic surface function has been obtained for the liner configuration. It was used to demonstrate a possible existence of closed magnetic surfaces in similar magnetic systems.

The numerical calculations have shown that the displacement of helical windings in the l=2 stellarator-type magnetic system does not cause an essential degradation of the magnetic surfaces. In the case under consideration their parameters do not practically differ from the parameters of the initial version of a similar l=2 torsatron.

It should be stressed, that in the l=2 stellarator under study, the magnetic surface configuration shifted inward the torus, with a planar magnetic axis, is realizable at the zero value of the transverse magnetic field. This restricts the problems of plasma formation free of inductively driven unipolar currents in the regime most favorable for plasma confinement.

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l=2 СТЕЛЛАРАТОР СО СМЕЩЕННЫМИ ВИНТОВЫМИ ОБМОТКАМИ

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Проведено изучение свойств конфигурации магнитных поверхностей в новой модели магнитной системы l=2 стелларатора со смещенными винтовыми обмотками. Смещение проведено с целью улучшения доступа к объему удержания плазмы. Показано, что благоприятная для удержания плазмы смещенная внутрь тора конфигурация магнитных поверхностей реализуется в отсутствие поперечного магнитного поля.

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l=2 СТЕЛАРАТОР ЗІ ЗМІЩЕНИМИ ГВИНТОВИМИ ОБМОТКАМИ

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Проведено вивчення властивостей конфігурації магнітних поверхонь в новій моделі магнітної системи l=2 стеларатора зі зміщеними гвинтовими обмотками. Зміщення запроваджено з метою покращення доступу до об’єму утримання плазми. Показано, що найбільш сприятлива для утримання плазми зміщена в середину тора конфігурація магнітних поверхонь реалізується за відсутністю поперечного магнітного поля.