MAGNETIC SURFACES OF AN *l*=4 STELLARATOR IN REGARD TO HELICAL COIL ANGULAR SIZE AND METHOD OF CONDUCTOR TURN PACKING

V.G. Kotenko

Institute of Plasma Physics, NSC "Kharkov Institute of Physics and Technology", Kharkov, Ukraine

Numerical studies were undertaken to elucidate the influence of the helical-coil finite angular size on *l*=4 stellarator magnetic surface characteristics. The calculations are applied to the closed magnetic surface configuration removed from the torus surface. The magnetic surface characteristics did not change significantly in comparison with ideal model of the *l*=4 stellarator magnetic system.
PACS: 52.55.Hc

1. INTRODUCTION

The *l*=4 stellarator is generally referred to the class of helical magnetic systems applicable for plasma confinement [1, 2]. An analytical estimation [1] and numerical simulations [2] of an ideal model of the *l*=4 stellarator comprising filamentary helical coils have been carried out. They show a possibility to realize a magnetic surface configuration with a steeply growing angle of rotational transform near the configuration edge and a negligibly small value of the rotational transform angle in the central part of the configuration. Therefore, two comparable-in-volume regions with different plasma confinement can be formed in a magnetic plasma trap based on the *l*=4 stellarator magnetic system.

One of two regions (the inner one) is, in fact, a region of plasma confinement in a simple axisymmetric toroidal magnetic field.

In another (outer) region plasma confinement takes place in a toroidal magnetic field with rotational transformation of field lines.

It is not improbable [3] that a significant difference in the transport coefficients in these regions can lead to formation of a zone with decreased values of transport coefficients (transport barrier) and transition to high plasma confinement mode (H-mode).

Moreover, similar to the magnetic systems of *l*=2 and *l*=3 stellarators the magnetic system of the *l*=4 stellarator can provide a controllable and deep detachment of the closed magnetic surface configuration from the torus surface, i.e., plasma column-wall spacing [4].

Probably, the practical realization of the *l*=4 stellarator will create a need to determine the influence of a real finite size of helical coils on the basic characteristics of magnetic surfaces. In this paper magnetic surface characteristics are numerically studied for the *l*=4 stellarator with regard to the angular size of a single-layer helical coil and one of possible methods of conductor turn packing in the layer [5].

The main purpose of the study is to get a general idea about the tendencies in variations of *l*=4 stellarator magnetic surface characteristics when passing from the ideal magnetic system closer to the real one.

2. CALCULATION MODEL

The calculation model has the following parameters:

- toroidicity $\alpha=a/R_0=0.25$ (*a* and R_0 are the minor and major radii of the torus, respectively);
- *l*=4 is the polarity;
- *m*=2 is the number of helical winding pitches along the torus length;
- the number of conductor turns in each of 8 single-layer helical coils is 7 (56 in total).

Each helical coil comprises the base conductor turn lying along the base helical line. The last 6 conductor turns are wrapped beginning with the base line on the both sides symmetrically of it (in the ideal model the helical coils comprise the base conductor turn only).

The base helical line is marked up on the torus according to the cylindrical winding law:

$$\theta(\varphi)=m\varphi, \quad (1)$$

where φ is the toroidal and θ is the poloidal angle.

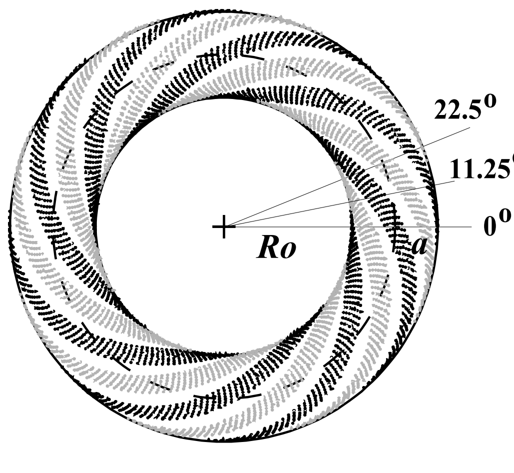

Fig.1. Top view of the helical coils (shaded) of the l=4 stellarator calculation model. The toroidal azimuths of poloidal cross-sections are indicated (see Fig. 2)

The angular size of helical coil measured along the minor torus equator is close to the maximum possible value, $\Delta\varphi \sim \pi/lm$.

With the described method of packing, the points of the helical line of the *n*th conductor turn shift relative to the points of the helical base line with regular intervals counted along the torus parallels. So, the linear size of each helical coil measured along one of the torus parallels is the constant value, $\Delta S = R_0(1-\alpha)\Delta\varphi$ (see Fig. 1).

The helical coil system is plunged into toroidal axisymmetric magnetic field $B_\varphi = B_0R_0/R$, where B_0 determines the value of the toroidal magnetic field on the circular axis of the torus, R is the observation point radius counted from the major axis (z-axis) of the torus.

The transverse magnetic field is assumed to be absent, $B_z=0$.

3. COMPUTATIONAL RESULTS

Fig. 2 shows poloidal cross-sections of the magnetic surface configuration calculated in the $l=4$ stellarator model with taking into account the single-layer helical coil angular size and the described method of conductor turn packing in the layer. The cross-sections are spaced by the toroidal angle φ within the limits of the magnetic field half-period $\varphi=0^o$, 11.25^o, 22.5^o (see Fig. 1). The results of simulation concern the magnetic surface configurations moved away from the torus surface, $r_{lc}/a \sim 0.4$ (r_{lc} is the average radius of the last closed magnetic surface). For the given value of the toroidal magnetic field B_o this can be reached by variation of the helical coil current.

The points and circles in Fig.2 mark the position of thin current-carrying conductors with alternate current directions forming the helical coils of the calculation model. They are located on the torus surface $a/R_0=0.25$ (thin circles).

It is seen from Fig. 2 that in all three cross-sections the closed toroidal magnetic surfaces (dotted lines) are rather well centered and have a square contour in the edge region of the configuration. This is an evidence of a higher helical symmetry stability of the $l=4$ stellarator magnetic field relative to the perturbation caused by bending of the straight magnetic system into the toroidal one.

Fig. 2 also shows the calculated cross-sections of the equiconnect surface [6] (solid curves). The equiconnect surface is a surface of the outer boundary of the stochastic layer of field lines, i.e. the outer boundary of the plasma layer with transient plasma parameters, the so-called scrape-off layer (SOL) plasma. The positioning of the equiconnect cross-sections may by useful to prevent direct interaction of the SOL plasma with the vacuum chamber wall, the radiofrequency units used for plasma generation and heating and with diagnostic tools.

The magnetic surface parameters as functions of their average radii are shown in Fig. 3 by solid lines.

It can be seen from Fig. 3a that the rotational transform angle is negligibly small, $i<10^{-2}$-10^{-3} (in 2π units), in the central part of the magnetic surface configuration, $r/r_{lc}<0.5$ (inner region). In the outer region, $r/r_{lc}>0.5$, its value is steeply growing to $i\sim 0.47$ (0.5) on the last closed magnetic surface, $r_{lc}/R_0=0.112$ (0.103). Here, the shear value is several times higher than standard one in the $l=2$ or $l=3$ helical magnetic systems. In the outer region a moderate value of the magnetic well, $-U=0\rightarrow 0.026$ (0.018), is observed (Fig. 3b and c) the field ripple $\gamma=1.1\rightarrow 1.33$ (1.3). The characteristics of the ideal model of the $l=4$ stellarator are presented in brackets.

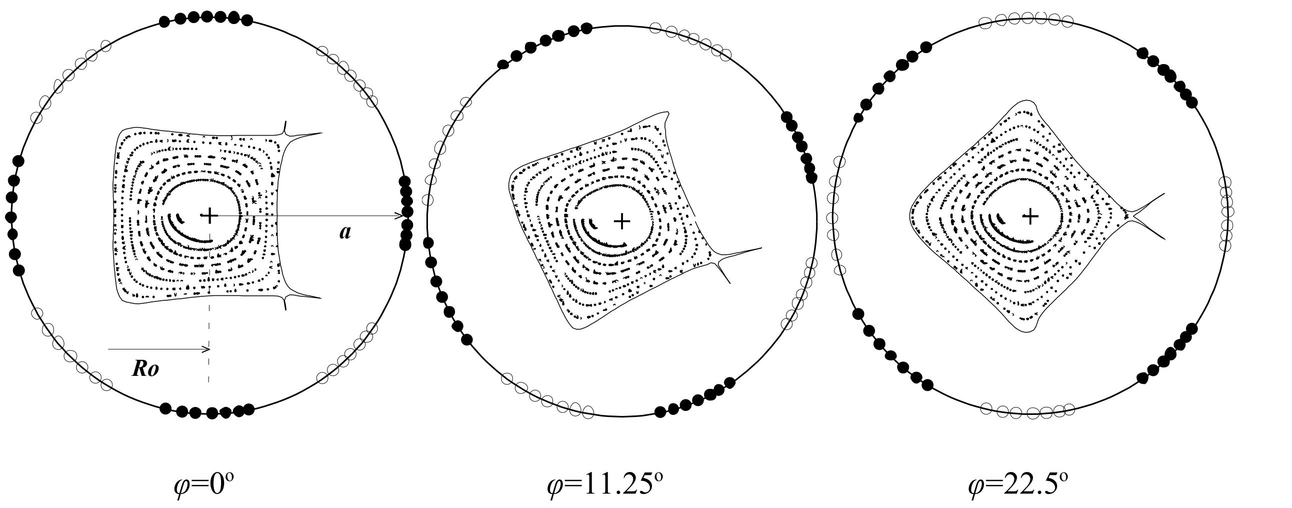

Fig.2. Cross-sections of magnetic (dotted lines) and equiconnect surfaces (the surface of the outer boundary of stochastic layer of field lines, i.e. the outer boundary of a plasma layer with transient plasma parameter, the so-called scrape-off layer (SOL) plasma, solid lines) in the l=4 stellarator calculation model within the limits of the magnetic field half-period (see Fig.1)

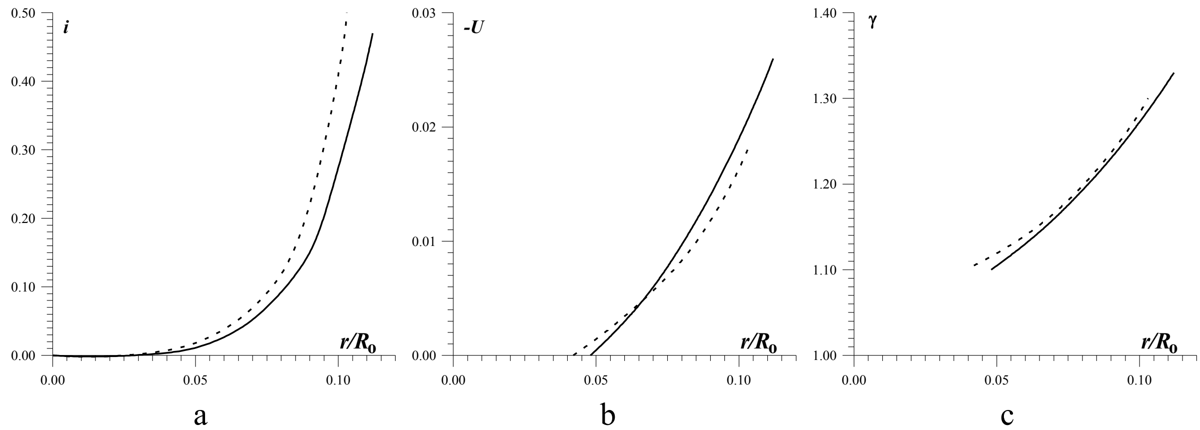

Fig.3. Rotational transform angle (a), magnetic well (b), field ripple (c) as functions of the average magnetic surface radius for the "real" (solid lines) and ideal (dashed lines) model of the l=4 stellarator

4. SUMMARY

The numerical calculations having been performed demonstrate that in the *l*=4 stellarator model with helical coils of finite angular size the magnetic surface characteristics such as the rotational transform angle, maximum field ripple value and the average radius of the last closed magnetic surface differ less than ~10% of the value inherent in the ideal model of the *l*=4 stellarator comprising filamentary helical coils. Also, the magnetic surface position and shape and form of the rotational transform angle radial dependence do not have a noticeable change. One can only observe a magnetic well increase by a factor of 1.5. Owing to the form of the equiconnect, the SOL plasma-wall interaction is supposed to be reduced in a plasma trap based on the *l*=4 stellarator magnetic system.

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Article received 22.09.08
Revised version 7.10.08

МАГНИТНЫЕ ПОВЕРХНОСТИ 4-ЗАХОДНОГО СТЕЛЛАРАТОРА С УЧЕТОМ УГЛОВОЙ ШИРИНЫ ВИНТОВЫХ ОБМОТОК И СПОСОБА УКЛАДКИ ПРОВОДНИКОВ

В.Г. Котенко

Проведено численное изучение влияния конечной угловой ширины винтовых обмоток на свойства магнитных поверхностей в 4-заходном стеллараторе. Расчеты относятся к конфигурации замкнутых магнитных поверхностей, удаленных от поверхности тора. Свойства магнитных поверхностей по сравнению с идеальной моделью 4-заходного стелларатора существенно не изменились.

МАГНІТНІ ПОВЕРХНІ 4-ЗАХОДНОГО СТЕЛАРАТОРА З УРАХУВАННЯМ КУТОВОЇ ШИРИНИ ГВИНТОВИХ ОБМОТОК ТА СПОСОБУ УКЛАДКИ ПРОВІДНИКІВ

В.Г. Котенко

Виконано чисельне дослідження впливу скінченної кутової ширини гвинтових обмоток на властивості магнітних поверхонь в 4-заходному стелараторі. Розрахунки торкаються конфігурації замкнутих магнітних поверхонь, віддалених від поверхні тора. Властивості магнітних поверхонь в порівнянні з ідеальною моделлю 4-заходного стеларатора суттєвих змін не зазнали.