EFFECT OF TOROIDAL MAGNETIC FIELD RIPPLE VALUE ON THE *l*=1, *m*=1 YAMATOR MAGNETIC SURFACES

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To form a ripple toroidal magnetic field, the calculated l=1, m=1 Yamator model is equipped with N=16 toroidal magnetic field coils of a_c radius. In order to study the effect of toroidal magnetic field ripple value δ on the magnetic surface parameters the calculation was performed for different values of radius a_c. In the paper the range of a_c radius values is identified within the scope of which the magnetic surface parameters are close to that of the l=1, m=1 Yamator with ideal axially symmetric toroidal magnetic field (δ=0).

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INTRODUCTION

The stellarator-type magnetic system, named as Yamator, is interesting due to the opportunity of forming a toroidal closed magnetic surface configuration with a high value of the averaged magnetic well, $-U$ ~ 0.1…0.5 [1, 2]. However, the high numerically calculated parameter values have been obtained under conditions that superposition of helical coil magnetic field and ideal axially symmetric toroidal magnetic field (TF) occurs. So, the calculations did not consider an inevitable appearance of TF ripples in the case of Yamator magnetic system practical realization and a possible effect of TF ripple values on the magnetic surface configuration. Ripple-induced helical magnetic field violation follows from the analytical study results [3, p. 56].

In the present paper the numerical calculations were carried out on the Yamator magnetic field formed by superposition of helical coil magnetic field and rippled TF generated by the system of N circular discrete TF coils with radius a_c. In order to study the effect of TF ripples on the magnetic surface parameters the calculations were performed for several Yamator magnetic systems having different values of TF coil radius a_c**.** The final goal of the study is to define the bounds of coil radii a_c within the range of which the effect of TF ripples on the inner magnetic surface parameters can be neglected. The revealed [1, 2] magnetic surface configuration, being outer against the helical coils in the Yamator with an unbounded ideal axially symmetric TF is not realized in the Yamator with the system of N circular discrete coils as a TF proper value extends not far then radius a_c.

CALCULATION MODEL

An ideal magnetic system of the simplest (l=1, m=1) Yamator with filament-like conductors has been chosen as a calculation model (Fig. 1,a,b). The l=1 polarity helical coils 1, 2 are wound around the surface of two coaxial torus having the same major radius R_0 and different minor radii a_1/R_0=0.3 and a_2/R_0=0.4. Each of helical coils is wound around the torus according to the law θ=mφ, where θ is the poloidal angle, φ is the toroidal angle, m=1 is the number of helical coil pitches along the torus length. The helical coil currents are equal-in-magnitude and opposite-in-direction. The amplitude of the circular-axis R_0 magnetic field generated by helical coil 1 is b_{01}.

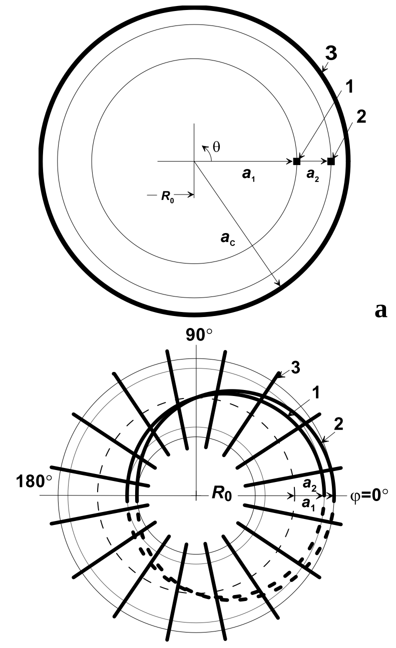


Fig. 1. Poloidal cross-section φ=0° (a) and top view (b) of the l=1, m=1 Yamator calculation model: 1, 2 – helical coils; 3 – TF circular discrete coils, θ is the poloidal angle, φ is toroidal angle. In the cross-section the discrete coil contour is also indicated (a_c radius)

The TF value $B_φ$ in the l=1, m=1 Yamator model was formed by the use of the N=16 circular discrete coils of radius a_c being coaxially and uniformly distributed along the circular axis R_0.

Fig. 2,a shows typical behavior of TF value $B_φ$ on the field line in the system of N=16 circular discrete coils (solid line) and on the field line of ideal axially symmetric TF (dashed line) on one go-round along the length of the torus (φ=0…360°). The TF ripple value in the system of discrete coils depends on the number N of TF coils as well as on the value of its radius a_c, and the value of the tested field line radial position R/R_0. The radial position R/R_0 is counted from the straight torus axis Z in the torus equatorial plane (Z=0). The resulting change in the relative TF ripple value, $δ=(B_{φmax}-B_{φmin})/(B_{φmax}+B_{φmin})$, versus the field line radial position R/R_0 in the systems of N=16 circular discrete coils having different radii a_c (a_c/R_0=0.35; 0.4; 0.45; 0.5) can be seen in Fig. 2,b.

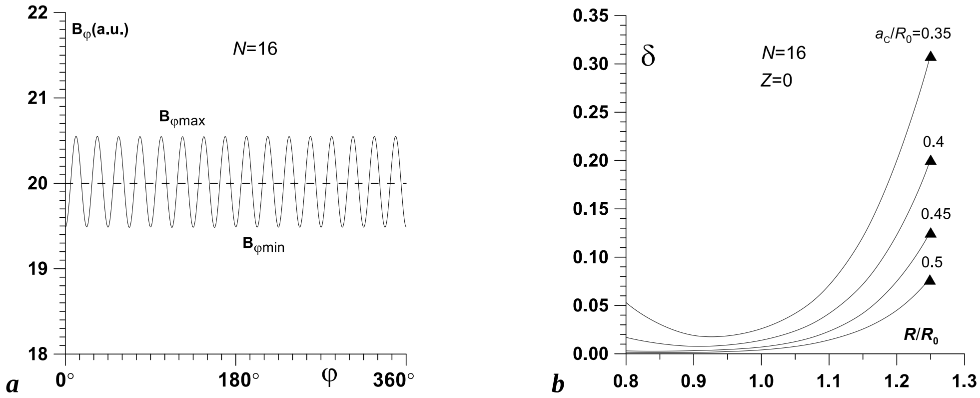


Fig. 2. Typical behavior of TF value B_φ on a field line (a) and the-magnetic field ripple relative value, $\delta=(B_{\varphi max}-B_{\varphi min})/(B_{\varphi max}+B_{\varphi min})$, as function of the field line radial position R/R_0 (b)

RESULTS OF CALCULATIONS

As a result of calculations the values of the magnetic surface parameters in the l=1, m=1 Yamator with an ideal axially symmetric TF and in the l=1, m=1 Yamator with system of N=16 circular discrete coils were obtained. Both of the Yamator magnetic surface configurations were formed under conditions of the constant ratio $B_\varphi(R_0)/b_{01}=10$ and complete absence of the vertical compensating magnetic field, $B_z/b_{01}=0$.

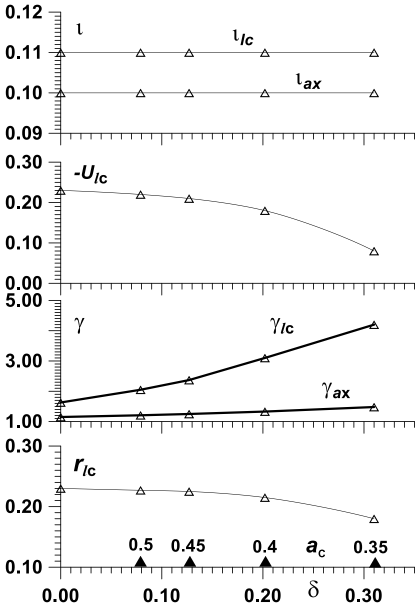


Fig. 3. Magnetic surface parameters as a function of the TF ripple relative value δ

Fig. 3 presents the calculated magnetic surface parameter values as a function of the maximum relative TF ripple value δ in the R/R_0 interval (▲ – points, see Fig. 2,b). If δ=0, the parameter values are related to the l=1, m=1 Yamator with an ideal axially symmetric TF, the parameter designations have an additional lower index "0". It is seen from see Fig. 3 that the average radius r_{lc} of the last closed magnetic surface in the Yamator with discrete coils decreases to r_{lc}/R_0=0.18 for δ=0.31 (a_c/R_0=0.35). For δ~0.1(a_c/R_0=0.5, 0.45) the r_{lc}/R_0 value is almost the same as r_{lc0}/R_0=0.23 in the Yamator with an ideal axially symmetric TF (δ=0).

As δ increases the mirror ratio γ ($\gamma=B_{max}/B_{min}$, where B_{max}, B_{min} denote the maximum and minimum magnetic field value) on the magnetic axis γ_{ax} and on the last closed magnetic surfaces γ_{lc} is appreciably increasing. If δ=0, γ_{ax0}=1.15 and γ_{lc0}=1.63, while in the Yamator with discrete coils γ_{ax}=1.48 and γ_{lc}=4.1 for δ=0.31(a_c/R_0=0.35).

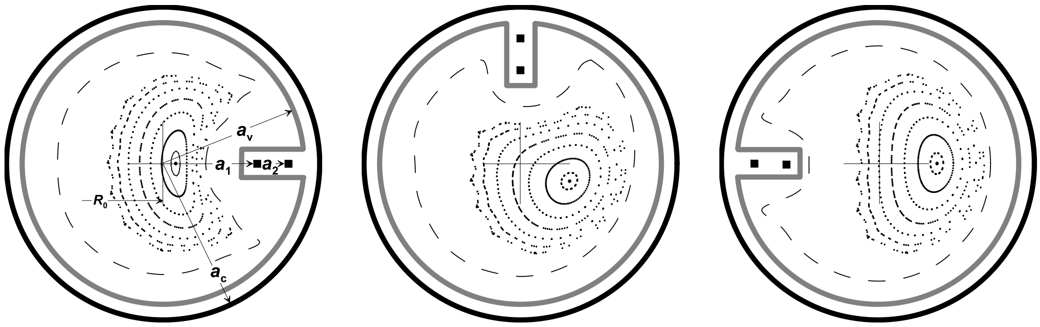
The magnetic well value on the last closed magnetic surface, $-U_{lc}\approx0.2$ for δ~0.1(a_c/R_0=0.5, 0.45), is slightly less than $-U_{lc0}$=0.23. For δ=0.31(a_c/R_0=0.35) the magnetic well value is three times less, $-U_{lc}\approx0.08$.

Any effect of the TF ripple value on the rotation transformation angle value ι (in units of 2π) on the magnetic axis (ι_{ax}) and on the last closed magnetic surface (ι_{lc}) was not revealed, $\iota_{ax}=\iota_{ax0}$=0.1 and $\iota_{lc}=\iota_{lc0}$=0.11.

The results obtained in the context of the paper objective testify to the effect that in the case of a practical realization of the l=1, m=1 Yamator with N=16 coils the value of the coil radius a_c should not to lower appreciably from a_c/R_0=0.5. This makes it possible to avoid a significant degradation of the magnetic surface parameter, in particular, of the magnetic well value, as compared with the magnetic surface parameters in the l=1, m=1 Yamator with an ideal axially symmetric TF.

In Fig. 4 the calculated magnetic surface cross-sections in the l=1, m=1 Yamator with system of N=16 circular discrete coils of a_c/R_0=0.5 radius are shown. The cross-sections are spaced through the toroidal angle φ within the limits of the magnetic field half-period, φ=0º, 90º, 180º. The average radius r_{lc} of the last closed magnetic surface (LCMS) is r_{lc}/R_0=0.22(0.23). The mirror ratio on the magnetic surfaces, $\gamma_{ax}\to\gamma_{lc}$=1.2(1.15) → 2.0(1.63), the magnetic well on the closed magnetic surface $-U_{lc}$=0.21(0.23), the rotational transformation angle is $\iota_{ax}\to\iota_{lc}$=0.1(0.1)→0.11(0.11), i.e. the magnetic surface configuration remains shearless. The corresponding parameter values of the magnetic surface in the calculated l=1, m=1 Yamator model with an ideal axially symmetric TF (δ=0) are indicated in brackets.

See Fig. 4 also shows the cross-sections of the vacuum chamber (radius a_v/R_0=0.45) with a helical flute for helical coils and the discrete coil contours (radius a_c/R_0=0.5).



φ=0° 90° 180°

Fig. 4. Poloidal cross-sections of the magnetic surfaces in the l=1, m=1 Yamator with N=16 discrete coils. The discrete coil contours are shown (a_c/R_0=0.5 radius). The vacuum chamber cross-sections are represented by the clarified line (a_v/R_0=0.45 radius)

The dashed lines show the cross-sections of the outer boundary of the stochastic field line layer [4], i.e. the boundary of the plasma layer having the transient plasma parameters (SOL plasma). It is seen from the figure that the calculated stochastic field line layer boundary does not intersect the vacuum chamber with radius a_v/R_0=0.45 in the ideal magnetic system of the *l*=1, *m*=1 Yamator with filament-like conductors.

CONCLUSIONS

In the present work the numerical study of the *l*=1, *m*=1 Yamator magnetic field, the toroidal component of which is produced by the system of *N*=16 circular discrete coils of radius a_c has been carried out. The calculations show that some magnetic surface parameters in the *l*=1, *m*=1 Yamator with a system of *N*=16 circular discrete coils (compared to the *l*=1, *m*=1 Yamator with an ideal axially symmetric TF) can be subjected to the appreciable degradation because of the TF ripple formation. The calculations also show that in the ideal *l*=1, *m*=1 Yamator magnetic system, comprising filament-like helical coils and *N*=16 circular discrete coils, the effect of TF ripples on the magnetic surface parameters is minimal if the circular discrete coil radius is $a_c/R_0 \approx 0.5$. The results received are not applied automatically to the other Yamators with $lm \neq 1$ and in particular to a magnetic field line behavior in the edge of the closed magnetic surface existence region.

The next step ahead in the development of the *l*=1, *m*=1 Yamator practical realization conception includes the study of the influence of finite-size transverse dimensions of the helical coils and TF coils on the magnetic surface parameters and the outer boundary of the stochastic field line layer.

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ВЛИЯНИЕ ВЕЛИЧИНЫ ГОФРА ТОРОИДАЛЬНОГО МАГНИТНОГО ПОЛЯ НА МАГНИТНЫЕ ПОВЕРХНОСТИ *l*=1, *m*=1 ЯМАТОРА

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Чтобы сформировать гофрированное тороидальное магнитное поле, расчетная модель *l*=1, *m*=1 яматора была снабжена *N*=16 круглыми катушками радиусом a_c. Для изучения влияния величины δ гофра тороидального магнитного поля на параметры магнитных поверхностей численные расчеты производились при различных значениях радиуса a_c. Определен интервал радиусов a_c, в пределах которого параметры магнитных поверхностей в яматоре с катушками близки к параметрам магнитных поверхностей в яматоре с идеальным осесимметричным тороидальным магнитным полем (δ=0).

ВПЛИВ ВЕЛИЧИНИ ГОФРУ ТОРОЇДАЛЬНОГО МАГНІТНОГО ПОЛЯ НА МАГНІТНІ ПОВЕРХНІ *l*=1, *m*=1 ЯМАТОРА

В.Г. Котенко, Г.Г. Лесняков, С.С. Романов

Щоб сформувати гофроване тороїдальне магнітне поле, розрахункова модель *l*=1, *m*=1 яматора була споряджена *N*=16 круглими котушками радіусом a_c. З метою вивчення впливу величини δ гофру тороїдального магнітного поля на параметри магнітних поверхонь чисельні розрахунки проводилися при різних значеннях радіуса a_c. Визначено інтервал радіусів a_c, в межах якого параметри магнітних поверхонь в яматорі з котушками близькі до параметрів магнітних поверхонь в яматорі з ідеальним осесиметричним тороїдальним магнітним полем (δ=0).