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Confinement Analysis of Low Aspect Ratio Tokamak-Stellarator Hybrid Configurations
低アスペクト比トカマク - ステラレーター混成配位の閉じ込め解析

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We proposed 6 types of low aspect ratio tokamak-stellarator hybrid configurations with a few helical coils wound on spherical or cylindrical boundary. We call these configurations ''TOKASTAR''. In this study these configurations are analyzed by computational simulation and experiment, and the connections between the parameters of magnetic flux surface and equilibrium beta or confinement capability of single high-energy particle of TOKASTAR are studied. We found that they can produce low aspect ratio flux surface with high elongation and the *N*=1 configuration achieved the highest equilibrium beta value among 6 types.

1. Introduction

Fusion reactor has several serious problems to be overcome for achieving commercial fusion reactor. It requires low capital cost, steady-state operation and good confinement capability of fusion plasmas. To solve these problems at the same time a new magnetic configuration concept is proposed [1], which is a low aspect ratio tokamak-stellarator hybrid configuration with a few simple helical coils wound on spherical or cylindrical boundary. We call these configurations ''TOKASTAR''. The coil design concept of TOKASTAR is shown in Fig. 1 and *N* in the caption is the toroidal mode number of helical coils. In the previous study the configuration with the shape of coils shown in Fig. 1 is analyzed in terms of magnetic flux surface formation, confinement capability of single particle and equilibrium beta by computational simulation, and the requirement for optimizing configuration is suggested [2].

In this study, we proposed 5 new TOKASTAR configurations shown in Fig. 2 and compared them with the previous study from the same view point. The aim of this study is to find out the connections between the parameters of magnetic flux surface and equilibrium beta or confinement capability of single high-energy particle of TOKASTAR.

2. Analysis Methods

2.1 *Computation method*

We analyzed TOKASTAR configurations by computational simulation code. We studied the vacuum magnetic flux surface and the plasma equilibrium state.

For magnetic flux surface analysis, we used the HSD code. This code traces a magnetic field line produced by the coils and defines the vacuum magnetic flux surface. The guiding center orbit of single high-energy particle is also computed in this code. This code solves the particle drift equation

$$\vec{v} = v_{//}\frac{\vec{B}}{B} + \frac{m}{qB^3}\left(\frac{1}{2}v_\perp^2 + v_{//}^2\right)\vec{B}\times\nabla\vec{B} \qquad (1)$$

In this computation, we used filament coil model. Plasma current and pressure were not considered when we used this code.

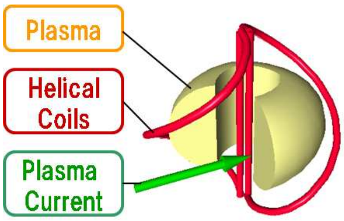
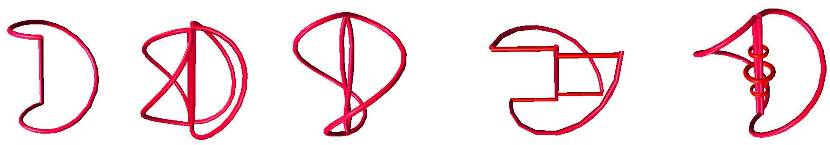


Fig.1. Concept of *N*=2 TOKASTAR



(a) *N*=1 (b) *N*=4 (c) *N*=2 with central helix (d) *N*=2 cylindrical coil system (e) *N*=2 with crescent cross-section

Fig.2. Concept design of 5 new TOKASTAR configurations

For equilibrium analysis, the VMEC code was utilized. The finite-beta 3-dimenional equilibrium was solved with the results of flux surface analysis by this code. The computational procedure of VMEC is to minimize the total energy of a plasma confined in a toroidal domain. The equilibrium states with finite-beta plasmas and the effects of plasma current in TOKASTAR configurations were analyzed with this code.

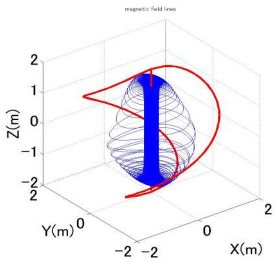
2.2 *Experimental method*

We carried out electron confinement experiment in TOKASTAR by impedance method. The details are going to be presented in the conference.

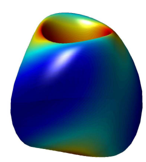
3. Results of Analysis and experiment

3.1 *Result of simulation of magnetic flux surface*

We carried out magnetic flux surface analysis for 6 types of TOKASTAR with HSD and VMEC codes and the results are shown in Fig. 3 and Table I. Figure 3 shows typical last-closed vacuum magnetic surface of N=2 TOKASTAR. Table I shows the shape parameters of cross-section of flux surfaces for 6 types of TOKASTAR. From these results we found out TOKASTAR can produce low aspect ratio configuration with high elongation.



(a)Vacuum magnetic field line (HSD code)



(b)3-D shape of surface (VMEC code)

Fig.3. Result of magnetic flux surface analysis of N=2 TOKASTAR.

Table I. Shape Parameters of magnetic flux surface

	A_p $(=R/a)$	$\langle A_p \rangle$ $(=R/\sqrt{ab})$	Ellipticity κ
N=2 (previous)	2.7	1.6	3.0
N=2 with central helix	2.5	1.4	3.3
N=2 with crescent cross section	5.3	2.6	4.1
N=2 cylindrical coil system	3.3	3.1	1.2
N=1	2.3	1.2	3.6
N=4	3.0	1.8	2.8

3.2 *Result of simulation of equilibrium*

In the equilibrium analysis with VMEC code, we researched equilibrium beta limit of TOKASTAR configurations. This beta limit is determined by convergence condition of VMEC and Shafranov shift condition: the beta value at which the magnetic axis shifts half way out to the last flux surface. The result of equilibrium beta limit analysis is shown in Fig. 4. In this figure, the vertical axis $\langle\beta\rangle_{\rm limit}$ indicates the volume-averaged equilibrium beta limit and the horizontal axis indicates the value of rotational transform at the plasma axis produced by plasma current. The radial dependence of the plasma current is assumed

$$\iota_{pl}(s)=\iota_{pl}(0)(1-s+1/3s^2), \qquad (2)$$

where s is normalized toroidal flux and $s\sim\rho^2$. In Fig. 4 the configuration N=1, which produces flux surface with the lowest $\langle A_p\rangle$ in Table I, achieved the highest equilibrium beta value within 6 types.

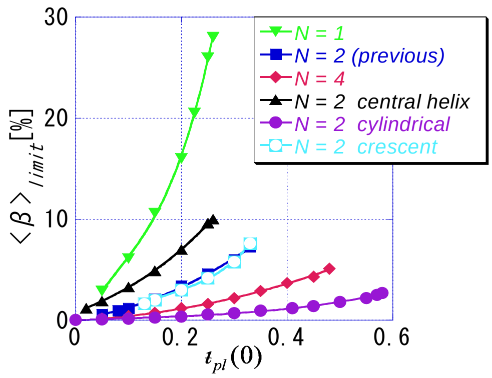


Fig.4. Equilibrium beta as a function of central rotational transform

3.3 *Result of simulation of particle confinement and experiment*

We analyzed electron and alpha particle confinement capability with HSD code and we compared these computational results with experimental result. The details are going to be presented in the conference.

4. Summary

We proposed and analyzed 6 types of TOKASTAR configurations and we found they can produce low aspect ratio flux surface with high elongation and the N=1 configuration with the lowest $\langle A_p\rangle$ achieved the highest equilibrium beta.

MHD stability and neoclassical transport of this TOKASTAR configuration will be clarified in the near future.

References

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[2] Y. Taira and K. Yamazaki *et al.*, Plasma and Fusion Research, Vol.5, S1025 (2010).