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Analyses and Experiments of Compact Spherical Tokamak-Stellarator "TOKASTAR"

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A hybrid configuration called TOKASTAR combined with a spherical tokamak and a compact stellarator has been proposed to make an easy start-up of tokamak plasma current operation and to reduce the probability of plasma current disruptions by external helical field. In this configuration a natural built-in divertor is provided. According to the finite beta equilibrium analysis, the higher equilibrium beta value can be attained by adding plasma current and increasing average rotational transform. The particle orbit analysis denotes that the high energy particle confinement is improved by increasing inboard-side rotational transform created by the central conductor modification from tokamak-like straight central post to helical winding post. The experimental preparation is performed for this TOKASTAR concept demonstration.

Keywords: spherical tokamak, stellarator, hybrid confinement, TOKASTAR, magnetic surface, finite-beta equilibrium, particle orbit

1. Introduction

According to the fusion reactor system analysis, for the realization of economic tokamak reactors, steady-state operation at high beta (>5%) should be achieved with high bootstrap current fraction (>70%) and efficient current drive methods. The system availability factor should be larger than 70 %, which gives rise to the requirements of only one permissible disruption during several years. For this purpose, reliable active disruption control is required in tokamak reactors. For compact and low-cost designs, a low-aspect-ratio system without disruptions might be created by some combinations among tokamak, helical and open field configurations. Moreover, easy maintenance of reactor system requires a simple coil system and enough plasma-coil space, which can be achieved using mirror field configurations.

Historically, a lot of exotic confinement concepts are proposed so far (Fig.1). One of the authors previously proposed the crescent-shaped tokamak-stellarator hybrid called TOKASTAR [1] in 1985 to improve the magnetic local shear near the bad curvature region and to get smooth transition from the first to the second stability regime against ballooning mode. At that time a reference system of N=4 configuration was proposed with outer

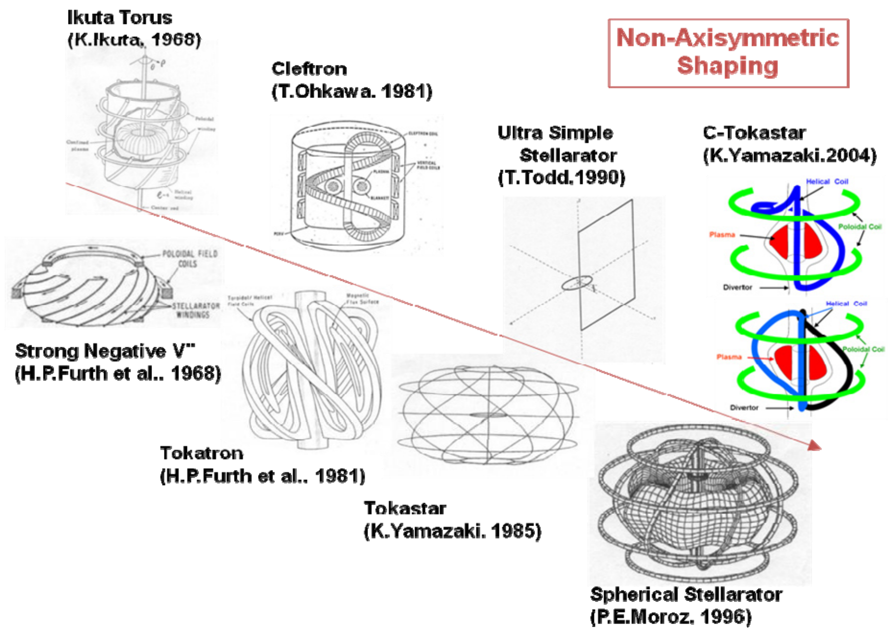

Fig.1. Proposal of TOKASTAR comparing with other compact helical configurations

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helical coils. After ten years a similar proposal of Spherical Stellarator [3] was proposed by Dr. S. Moroz in 1996.

As an extension of this TOKASTAR, we propose an N=1 or N=2 compact coil system C-TOKASTAR (Compact Tokamak/Stellarator Hybrid) [2]. This system has several advantages: (1) probable high-beta by strong magnetic well, (2) steady-state operation by helical coils, (3) no current disruption risk by external helical field, (4) enough divertor space by mirror-type magnetic divertor configuration, (5) compact economic system by spherical configuration, (6) easy maintenance by simple N=1 or N=2 coil system.

Here, firstly we show the theoretical modeling of this configuration and denote the analysis results about magnetic surface, equilibrium and particle orbit analyses. The experimental preparations for C-TOKASTAR and TOKASTAR-2 are described in Section 3, and the summary and discussions are given in the final section.

2. Theoretical Modeling

In the configuration analysis, magnetic field tracing code HSD [4] is used to define vacuum magnetic surfaces and divertor configuration, and the DESCUR code is used to obtain Fourier mode spectra of the vacuum last closed magnetic flux surface (LCMFS). The finite-beta 3-dimensional equilibrium was solved by the VMEC code [5], and the effects of current-free or flux-conserving high-beta plasmas configuration were evaluated [6]. The particle orbit analysis is also carried out by guiding-center theory using HSD-orbit code.

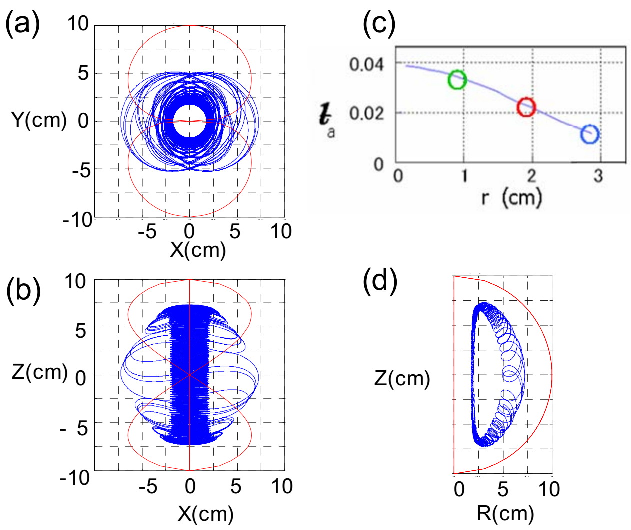

Fig.2 N=2 TOKASTAR coil system and closed magnetic field lines ((a) plan and (b) side view). The average rotational transform (c) as a function of plasma minor radius, and the magnetic field line traces (d) projected to one poloidal vertical plane.

2-1. Magnetic Surface Analysis

The vacuum magnetic surfaces and divertor configuration of TOKASTAR is analyzed using filament coil model. The aspect ratio of the TOKASTAR plasma is 1.2, and the ellipticity is around 2.0 as shown in Fig.2 d). The typical vacuum maximum rotational transform $\iota_{max}/2\pi$ is 0.39 on the outboard side, and the average value $\langle\iota\rangle/2\pi$ is 0.012 as shown in Fig.2 c). For increasing rotational transform, one method is to introduce plasma current; other is to add the inboard-side rotational transform by the modification of center conductors.

2-2. Equilibrium Beta Analysis with plasma current

The finite-beta 3-dimensional equilibrium including plasma current is solved by the VMEC code, and the effects of current-free or flux-conserving high-beta plasmas configuration were evaluated. Figure 3 shows the comparisons between without (as seen in Fig.3 a)) and with (as seen in Fig.3 b)) plasma current. By adding the plasma current, the average rotational transport increases and the finite-beta radial-shift of the magnetic axis can be suppressed, which leads to the increase in the achievable equilibrium beta value, as shown in Fig.4. Here we should note that in order to realize disruption-free discharge the external transform $\iota/2\pi$ should be larger than 0.14, which condition was found in old W7A and JIPP-T2 experiments [7,8].

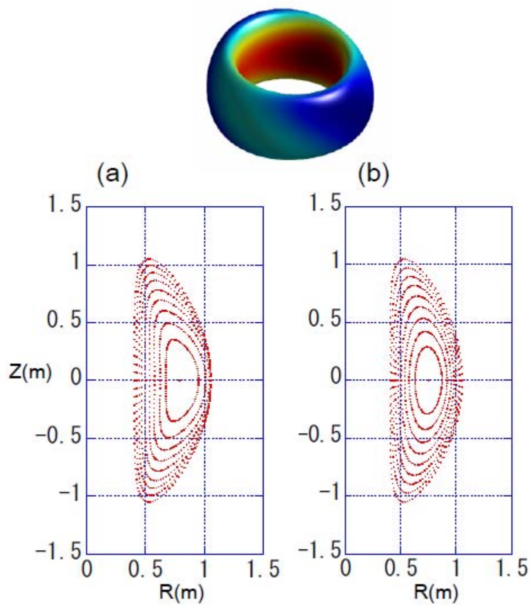

Fig.3 3-D equilibrium configuration (top) of TOKASTAR plasma calculated by VMEC code. Poloidal cross-section of flux surfaces (downside) of TOKASTAR with <β>~0.52% at toroidal angle ϕ=0.
(a):current-free equilibrium, (b): flux-conserving equilibrium with plasma current.

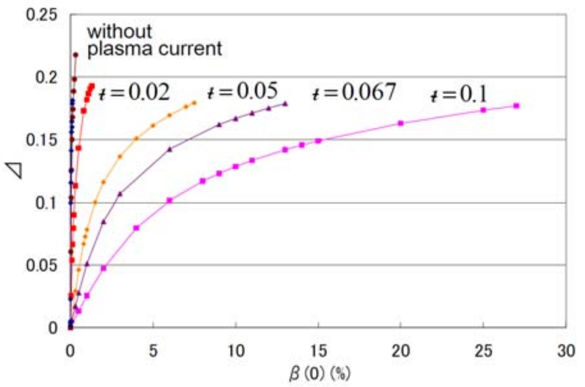

Fig.4 Effect of plasma current on the magnetic axis shift $\Delta = r_{shift} / a$ of Tokastar plasma equilibrium.

2-3. Particle Orbit Analysis

The particle orbit analysis using guiding orbit theory shows that the confinement of TOKASTAR is almost same or better than the N=6 conventional Heliotron configuration as shown in Fig.5 a) and b). In this comparison, the normalized Larmor radius with respect to plasma radius is set to almost same values. (r_L/a ~0.002-0.006). Here we adopted the particle loss boundary defined by the helical coil winding projection as shown in Fig.2 d). The loss boundary of N=6 system is also defined in the same manner.

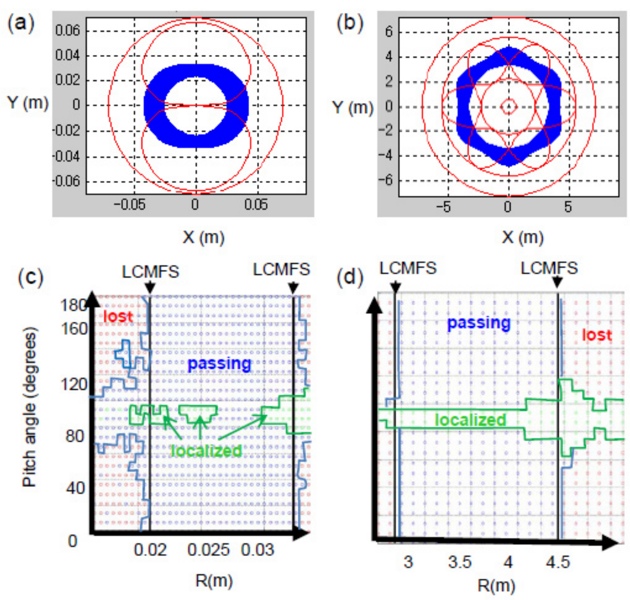

Fig.5 Particle orbit traces ((a) and (b)) and lost particle identification ((c) and (d)) from the coil boundary. LCMFS denotes last closed magnetic flux surface.
(a) ,(c):TOKASTAR with N=2 spherical coil system,
(b),(d) :N=6 standard Heliotron configuration with circular coil system.

By the helical modification of the central conductor, we can increase the inboard-side rotational transform and therefore can increase averaged rotational transform. Figure 6 denote the increase in the averaged central rotational transform by modifying axi-symmetric central coil systems into helical coil systems. In this case the radius of the last closed plasma surface becomes smaller by this central post modification. The fraction of lost particles is also shown at the bottom of this figure.

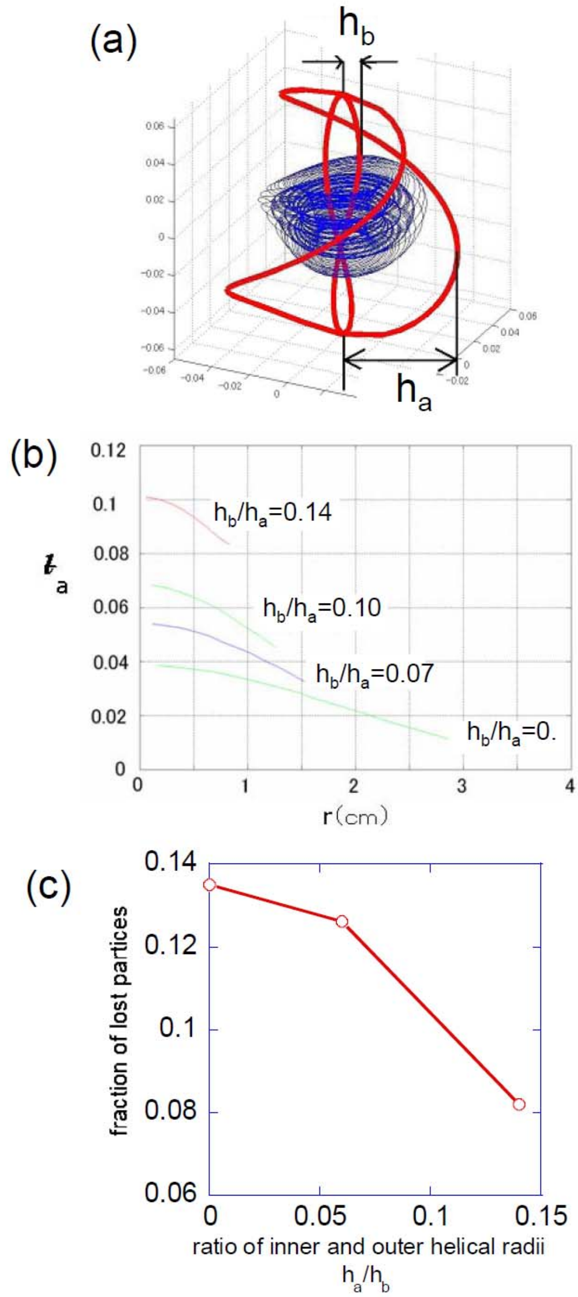

Fig. 6 Effect of helical deformation of inboard coil on the particle loss.
(a): coil system and particle orbit
(b): rotational transform increased by the helical central post.
(c): fraction of lost particles.

3. Experimental Arrangements

The relevant compact miniature experimental device C-TOKASTAR (major radius ~ 2 cm) [2] was constructed to demonstrate the confinement concept of this compact tokamak-stellarator hybrid configuration. Recently we are constructing a slightly larger machine TOKASTAR-2 (plasma major radius ~ 10 cm), which can operate in the pure tokamak mode. The details of plasma analysis and experimental progress on TOKASTAR will be presented in the conference

3-1. Miniature Machine C-TOKASTAR

To demonstrate the TOKASTA concept, we made a miniature device C-TOKASTAR. Two sets of helical coil and three sets of vertical coils can produce nice magnetic surfaces. Its plasma major radius Rp is ~2 cm, the spherical coil radius Rcoil is ~10cm, and the magnetic field strength at plasma center is B~0.1kG. Figure 7 shows glow plasma production in C-TOKASTAR and the impedance probe method with electron emission probe are tried for checking vacuum magnetic surfaces. At present it is not successful to identify the magnetic surface properties in this miniature machine, because even electron Larmor radius is same order of the plasma radius.

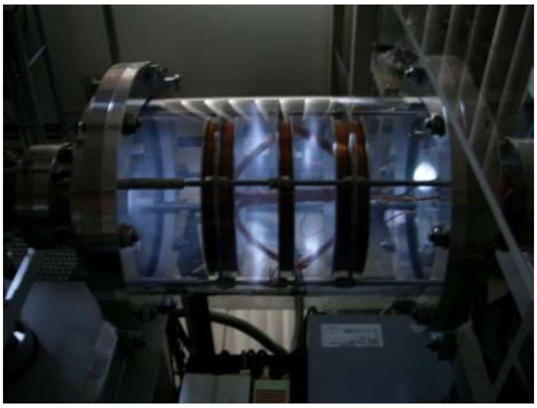

Fig.7 Photo of glow plasma production in C-TOKASTAR.

3-2. TOKASTAR-2 with Outer Helical Coils under Construction

In order to make plasma current flow in TOKASTAR, we are preparing TOKASTAR-2 machine (R~12 cm, BT~1kG) with OH central coil, eight toroidal coils and two outer helical coil segments (Fig.8) . The vacuum magnetic surface is also given in Fig. 8. These coils are installed in the vacuum cryostat except external vertical coils. The ECH plasma start-up and plasma current disruption control experiments might be expected in this machine.

4. Summary and Discussions

A compact spherical tokamak-stellarator hybrid called TOKASTAR has been proposed, and its vacuum and finite-beta magnetic surfaces are analyzed. The particle orbit analysis is also carried out. Here we conclude as follows;

(1) Using one or two helically twisted spherical toroidal coils, the clean magnetic surfaces with low aspect ratio are created.
(2) This configuration has natural built-in divertor.
(3) By adding plasma current, the higher equilibrium beta limit is obtained.
(4) The inboard-side rotational transform and therefore the average rotational transform are increased by the helical modification of central conductors.
(5) The particle orbit confinement is improved by the helical modification of the central post coil system.
(6) The experimental arrangements are under preparation with small C-TOKASTAR and TOKASTA-2 devices to demonstrate this concept.

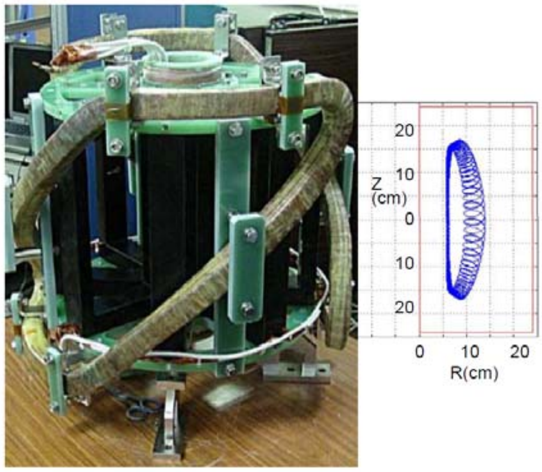

Fig.8 Photo of TOKASTAR-2 (under construction) with two outer helical coil segments, and its calculated magnetic surface of pure helical operation.

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