Analysis of Particle Orbits in a Spherical Tokamak-Stellarator Hybrid System (TOKASTAR) and Experiments in the Compact-TOKASTAR Device

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The compact spherical tokamak-stellarator hybrid system, TOKASTAR, has been proposed, and particle orbit analysis in this pure-stellarator configuration has been carried out. In the original configuration produced by an outboard-side helical coil and central straight coil post, the average rotational transform is rather small, and several improved configurations were evaluated. Improved confinement of charged particles was achieved by replacing the central straight coil post with an inboard-side helical coil system. To demonstrate the original configuration concept experimentally, the Compact-TOKASTAR device (C-TOKASTAR) was constructed, and the existence of magnetic surfaces and electron confinement are suggested using the stellarator diode method.

Keywords: TOKASTAR, tokamak, stellarator, hybrid system, magnetic surface, particle orbit

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1. Introduction

A tokamak magnetic configuration system is widely accepted as an attractive future toroidal fusion reactor because of its axisymmetric simple coil configuration and good plasma confinement properties. Its coil system is smaller and more compact than a helical coil system. However, to operate in the steady state, external power for the plasma current drive is required, and the risk of plasma current disruption should be considered. On the other hand, helical magnetic confinement systems are superior to tokamaks for steady-state operation and possible disruption-free operation, but their non-axisymmetric configuration properties result in the loss of fast ions. The compact spherical tokamak-stellarator hybrid system TOKASTAR has been proposed [1–3]; it is characterized by a compact, simple coil system, a natural divertor formation with sufficient space, and probable disruption-free operation. Similar proposals have been published, including CLEFTRON [4] and Spherical Stellarator [5]. However, no experimental trials have been done yet.

In this paper, we calculated improved TOKASTAR configurations with a higher external rotational transform to suppress plasma current disruptions and evaluated the characteristics of particle orbit confinement in pure-stellarator operation of the Compact-TOKASTAR device (C-TOKASTAR). Figure 1 shows the C-TOKASTAR concept with toroidal number N = 2. Two helical coils are combined at the center of the system, and one pair of poloidal coils is installed outside the helical coils to cancel the vertical magnetic field made by the helical coils.

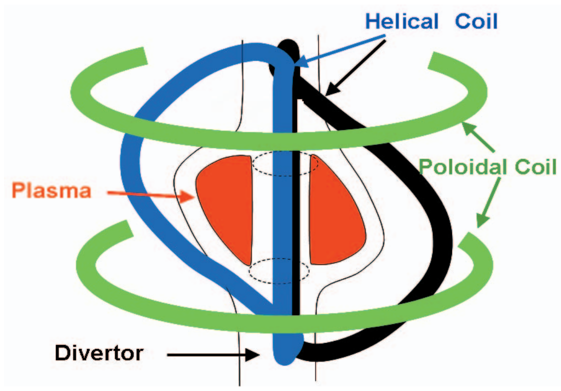

Fig. 1 N = 2 TOKASTAR concept.

Plasma can be confined in this system, and a natural divertor structure exists outside the last closed magnetic surfaces. The effects of plasma current on plasma equilibrium were given in Ref. [3], and tokamak-stellarator hybrid operations in TOKASTAR will be clarified in the next small experimental machine TOKASTAR-2 with ohmic plasma current [3].

2. Calculation method

In the configuration analysis, the magnetic field tracing code HSD (helical system design) is used to calculate the vacuum magnetic surfaces. We define the coil configuration and its electric coil current as input parameters and calculate magnetic field lines by Biot-Savart's law in the HSD code. The guiding-center drift-orbit approximation is used to calculate the orbit trajectory of fast ions. The following guiding-center equations for charged particles with

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mass m, charge e, and velocity $v_{//}$ parallel to the magnetic field (unit vector $\vec{b}$ and strength B) are integrated to calculate particle trajectories at time t and position $\vec{r}$ [6],

$$\frac{dv_{//}}{dt} = -\frac{{v_\perp}^2}{2B}(\vec{b}\cdot\nabla)B\,. \tag{1}$$

$$\frac{1}{v}\frac{d\vec{r}}{dt} = \frac{v_{//}}{v}\vec{b} + \rho\left(\frac{\beta^2}{2}\frac{B}{B_0} + \frac{{v_{//}}^2}{v^2}\right)\frac{B_0}{B}\left(\vec{b}\times\frac{\nabla B}{B}\right). \tag{2}$$

where

$$\rho = \frac{mv}{eB_0}\,, \quad \beta = \alpha\sqrt{\frac{B_0}{B_i}}\,. \tag{3}$$

Here, B_0 is the toroidal magnetic field at the magnetic axis, and the subscript$i$ denotes values at the initial starting point.

3. Analysis of magnetic surfaces and particle confinement in TOKASTAR system

In this TOKASTAR configuration, the outboard-side local rotational transform is large, but that on the inboard side is small. The average vacuum transform is defined by averaging these local transforms over magnetic field lines. The average vacuum rotational transform decreases as a function of the minor radius and is 0.038 near the magnetic axis. However, the average vacuum rotational transform is 0.01 at the last closed magnetic field surface (LCMFS). The vacuum external rotation transform of the present TOKASTAR system should be smaller than 0.14, which might be a critical value of disruption-free operation as demonstrated in the current-carrying stellarators WVII-A [7] and JIPPT-IIU [8]. Moreover, we can see that the vacuum rotational transform is very small (< 0.01) on the inner side of the system (q < −2 radian, q > 2 radian) and high (> 0.04) on the outer side of the system. Here, the position q = 0 denotes the outside horizontal plane. The reason the vacuum rotational transform is small on the inner side of the system is that this TOKASTAR system does not have helical magnetic components on the inner side.

Next, we studied particle-orbit confinement of fast ions in TOKASTAR (Fig. 2). The fast ions on the LCMFS are confined (passing particles), and some ions are localized around a pitch angle of 90 degrees. Moreover, in this research we show that many fast ions are lost at random outside of the LCMFS which are passing or localized in

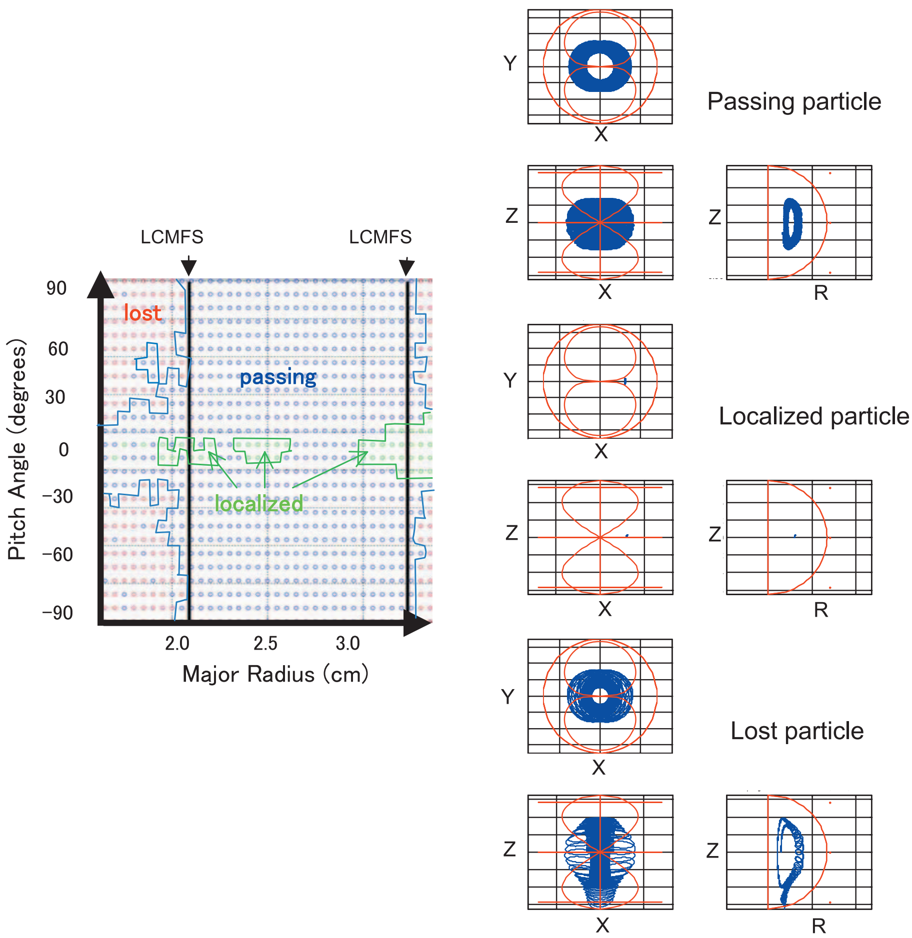

Fig. 2 Ion confinement diagram of TOKASTAR. Proton velocity is 440 m/s ($\rho_{ci}/a_p \sim 0.006$). Here, ρ_{ci} is the ion Larmor radius, and a_p is the plasma radius. Typical orbits of passing, localized, and lost particles are shown on the right.

TOKASTAR. A particle confinement comparison between this N = 2 TOKASTAR and the N = 6 standard heliotron configuration has already been done in Ref. [3].

This analysis is carried out to check electron confinement properties in the small experiment shown in Section 5, in addition to the investigation of its magnetic surface properties.

4. Proposal for improved TOKASTAR

We showed in Section 3 that C-TOKASTAR has a low vacuum rotational transform. To increase the rotational transform, we first propose an improved TOKASTAR with a helical component on the inboard side of the system, as shown in Fig. 3. In this figure, we define *ha* and *hb* as the outboard-side helical radius and inboard-side helical radius, respectively.

We show that, with an increase in the ratio *hb/ha*, the vacuum rotational transform improves (Fig. 4). When *hb/ha* is 0.14, the rotational transform becomes ~0.1. However, with the increase in *hb/ha*, the plasma volume decreases.

Generally, when the average vacuum rotational transform increases, the deviation between the fast-ion orbit surface and the magnetic surface, Δ, will decrease, and fast ion confinement can be improved. We confirm the relationship between the rotational transform and the shift Δ. As shown in Fig. 5, the shift of the ion orbit surface against the magnetic surface normalized by the plasma minor radius, Δ/a_p, decreases as *hb/ha* is increased. When the vacuum rotational transform is 0.092, the shift Δ becomes nearly zero. In Table 1, we show the effect of inboard-side helical modifications on the rotational transform increase and loss

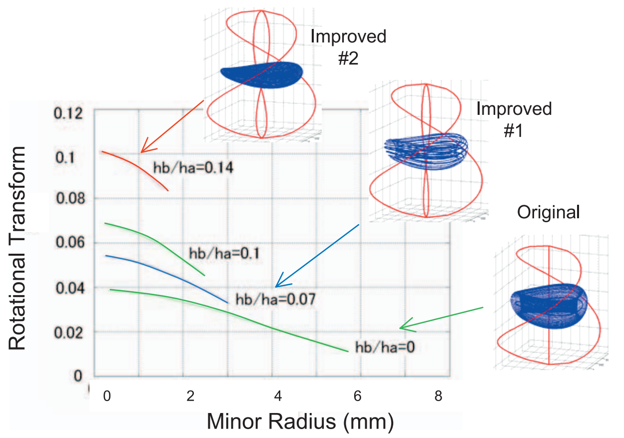

Fig. 4 Radial profiles of rotational transform in the improved TOKASTAR with central helical coil modification as shown in Fig. 3.

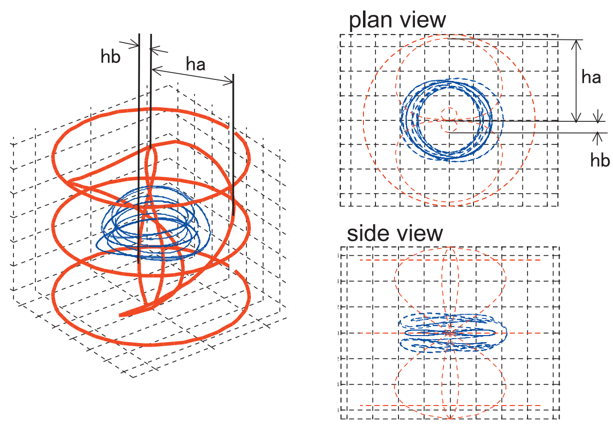

Fig. 3 Improved TOKASTAR with inboard-side helical coil post. Two magnetic surfaces are shown in the spherical helical coil system. Bird's eye view is shown on the left, and plan and side views appear on the right.

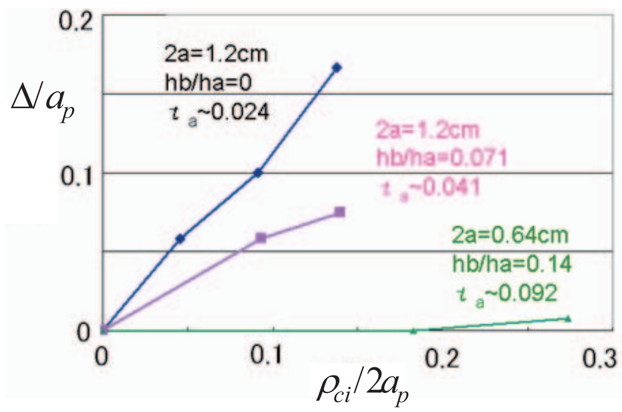

Fig. 5 Ion drift orbit surface deviation from magnetic surface Δ normalized by plasma minor radius a_p as a function of ion cyclotron radius normalized by plasma diameter $2a_p$.

Table 1 Fraction of lost particles in improved TOKASTAR configurations shown in Fig. 4.

	hb/ha	vacuum rotational transform at $r = a/2$	fraction of lost particles
Original Model	0	0.024	0.133
Improved Model #1	0.07	0.041	0.127
Improved Model #2	0.14	0.092	0.083

particle reduction in improved TOKASTAR systems. As this table shows, the increase in vacuum rotational transform leads to improved fast ion confinement. When *hb/ha* is 0.14, the fraction of lost particles is about 8.3 %. In this analysis, the fraction of lost particles was evaluated using the diagram of one poloidal plane in Fig. 2.

Second, we proposed the improved TOKASTAR Model #3, which reduces the magnetic ripples on the outer side of the TOKASTAR system. As shown in Fig. 6, a large outer coil system is adopted for this analysis. We move the outer helical field component away from the plasma, and the local magnetic ripple σ decreases on the outside of this system. For the improved TOKASTAR Model #3, $\sigma = 0.078$, and for the original configuration, $\sigma = 0.76$. We expected that the outer helical ripple reduction would improve fast ion confinement, but the fraction of lost particles increased by 66 %. This is because when we reduce the helical ripple component, the vacuum rotational transform decreases at the same time. So the present Model #3 is not effective for improving fast particle confinement.

Third, we proposed improved TOKASTAR Model #4 with four helical coils. It has a lower aspect ratio, A∼2, compared to A∼2.7 for the original TOKASTAR. The properties of this system will be presented in the future.

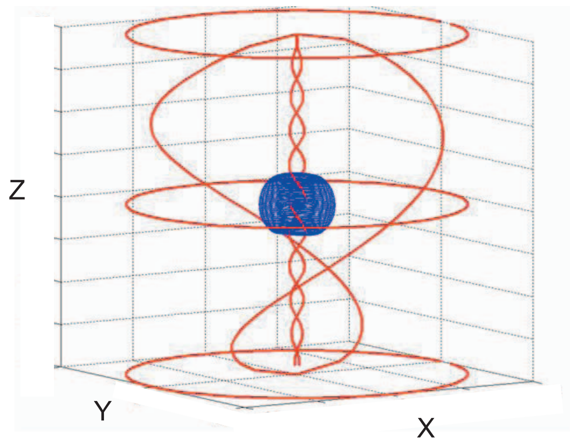

Fig. 6 Coil system and typical magnetic surface of improved Model #3.

5. Stellarator diode method in C-TOKASTAR experiments

To check the existence of magnetic surfaces and the electron confinement properties in C-TOKASTAR, an electron-emission impedance method (the stellarator diode method [9]) is used. C-TOKASTAR has double 10-turn helical coils and a pair of 20-turn poloidal coils. The typical major plasma radius is 35 mm, the radius of the poloidal coil is 70 mm, and the radius of the helical coil's spherical winding frame is 65 mm. As shown in Fig. 7, we insert an electron gun filament in C-TOKASTAR and detect the

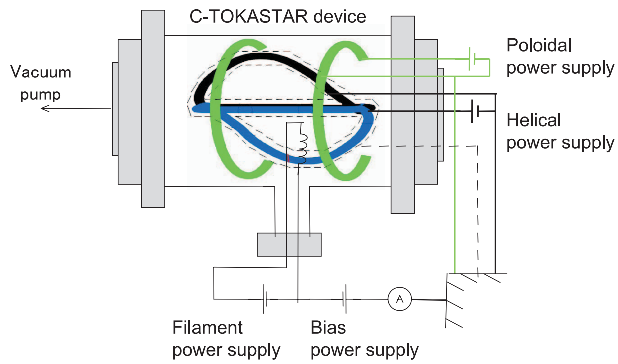

Fig. 7 Experimental layout of stellarator diode method in C-TOKASTAR.

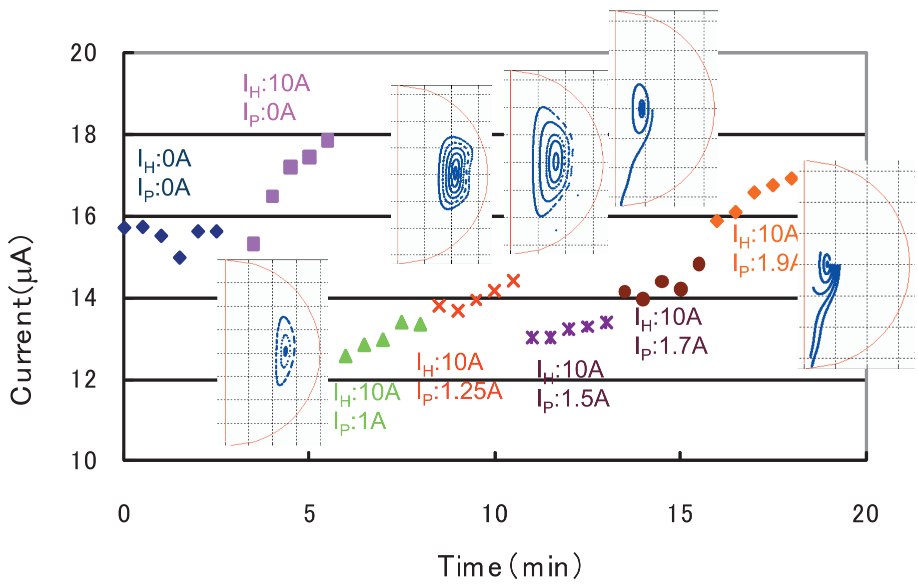

Fig. 8 Variation of quasi-steady electron emission current with changing magnetic configuration.

electron current. When the magnetic surface forms, the electrons go around the magnetic surface and finally exit to the ground. Therefore, a larger circuit impedance can be detected when magnetic surfaces exist than when magnetic surfaces have not formed. If the applied electric field is rather high (> several hundred volts) in this weak field machine (several tens of Gauss), electron orbit confinement is not good, which is confirmed in the drift orbit analysis shown in previous sections.

In Fig. 8, we show the results of the stellarator diode method. We light an electron gun filament for about 18 min, during which we change the helical coil current [I_H(A/turn)] and poloidal coil current [I_P(A/turn)]. In this experiment, the bias power supply voltage is 9.4 V. In this figure we also show the magnetic surfaces analyzed by the HSD code. When the coil current ratio I_H/I_P is between 6 and 10, magnetic surfaces form. The decrease in emission current due to application of a magnetic field agrees with the existence of closed magnetic surfaces. Using this stellarator diode method, we can confirm the influence of a magnetic field on electron confinement and suggest the existence of magnetic surfaces and electron confinement.

6. Conclusion

We analyzed fast particle orbits in a compact spherical tokamak-stellarator hybrid TOKASTAR. Several inboard-side helical coil modifications are proposed to improve particle confinement, and the particle loss reduction is clarified. A miniature machine, C-TOKASTAR, was constructed, and an electron-emission impedance method was applied to check magnetic surfaces. We found, by comparison with HSD analysis, that magnetic and particle orbit surfaces might form in this C-TOKASTAR device.

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