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Analysis of particle orbits in spherical tokamak-stellarator hybrid system (TOKASTAR) and experiments in Compact-TOKASTAR device

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A compact spherical tokamak-stellarator hybrid system TOKASTAR was proposed, and particle orbit analysis in this configuration has been carried out. In the original configuration, the average rotational transform is rather small, and several improved configurations were evaluated. The confinement improvement of fast particles was clarified. For the experimental demonstration of this configuration concept, a Compact-TOKASTAR device (C-TOKASTAR) was constructed, and the existence of these magnetic surfaces was suggested using an electron-emission impedance method.

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

1. Introduction

A tokamak magnetic configuration system is widely accepted as a future attractive toroidal fusion reactor, because of axisymmetric simple coil configuration, and good plasma confinement properties. It has smaller and more compact coil system than the helical coil system. However, to operate in steady state, external power for 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 operations, but non-axisymmetric configuration properties give rise to the loss of fast ions. Here, a compact spherical tokamak-stellarator hybrid system TOKASTAR was proposed[1,2], which has a compact and simple coil system and natural diverter[3].

In this paper, we evaluated characteristics of particle orbit confinement in a Compact-TOKASTAR device (C-TOKASTAR). Figure 1 shows the C-TOKASTAR concept with toroidal number N=2. Two helical coils are combined at center of the system and one pair of poloidal coils is installed outside of helical coils to cancel vertical magnetic field made by helical coils. Plasma can be confined in this system and a natural divertor surface exits outside the last closed magnetic surfaces [3].

2. Method of calculation

In the configuration analysis, magnetic field tracing code HSD (helical system design) is used to calculate vacuum magnetic surfaces. We define coil configuration and its electric coil current as input parameters, and

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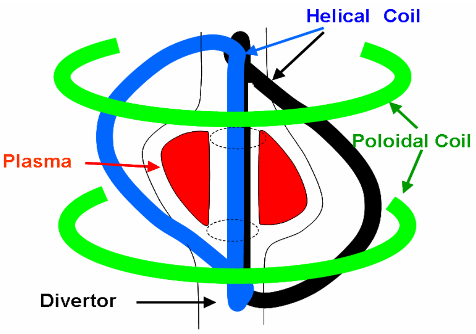

Fig.1 N=2 TOKASTAR Concept

calculate magnetic field lines by the Biot-savart's law in the HSD code. The guiding-center orbit theory is used to calculate the orbit trajectory of fast ions. The guiding-center equation which we used in this research is as follows;

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

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

where

$$\rho = \frac{mv}{eB_0}\ ,$$

$$\beta = \alpha\sqrt{\frac{B_0}{B_i}}$$

(B_0 is the toroidal magnetic field at magnetic axis, and the suffix i denotes values at starting point).

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

Figure 2 shows a schematic drawing of the analysis layout in the case of circular magnetic surfaces. Here, θ is poloidal angle, r is minor radius of plasma, and R is major radius. In this figure we divided cross-sections into 3 sections, "1/3 magnetic surface", "2/3 magnetic surface" and "LCMFS (last closed magnetic field surface)" from magnetic axis in order.

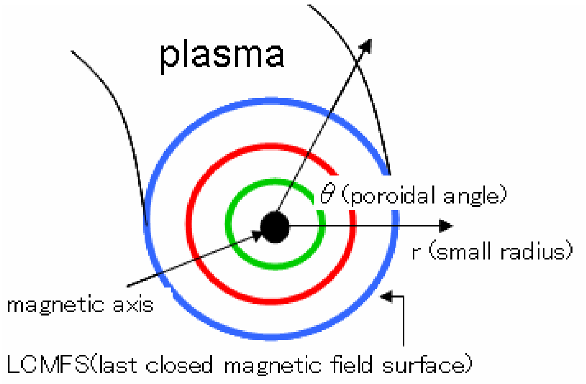

Fig.2 Layout of plasma analysis

The average and local vacuum rotational transforms are shown in Figs. 3(a) and (b), respectively. The average vacuum rotational transform decreases as a function of small radius. The vacuum rotation transform of the present

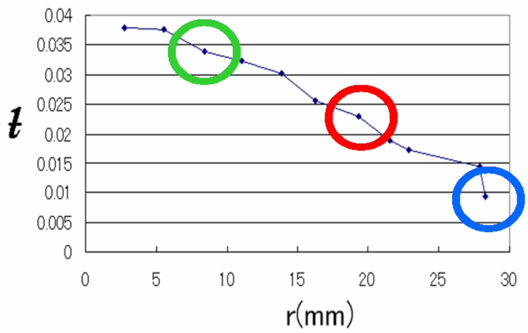

Fig.3(a) Average vacuum rotational transform in TOKASTAR. Colored circles corresponds to Fig.2

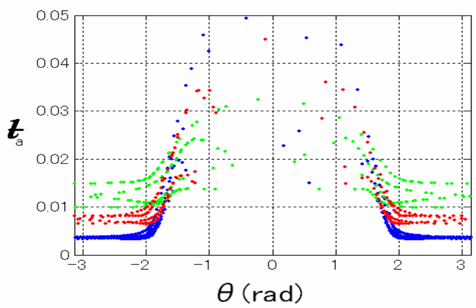

Fig.3(b) Local rotational transform as a function of poloidal angle θ in TOKASTAR

TOKASTAR system is smaller than 0.14 which might be a critical value of disruption-free operations. Moreover in Fig. 3(b), we can see the vacuum rotational transform is very small on the inner side of the system (θ < 2rad, θ > 2rad). The reason why the vacuum transform is small is TOKASTAR system does not have helical magnetic components inside this system.

Secondly, we studied confinement of fast ions in TOKATAR (Fig.4). The fast ions in LCMFS is confined (passing particles), and there are some ions which are localized in TOKASTAR system in pitch angle~90degrees domain. Moreover, in this research we show that there are many fast ions in random out of LCMFS which are passing or localized in TOKASTAR. The particle confinement comparisons with this N=2 TOKASTAR and the N=6 standard heliotron configuration has already been done in ref.[4].

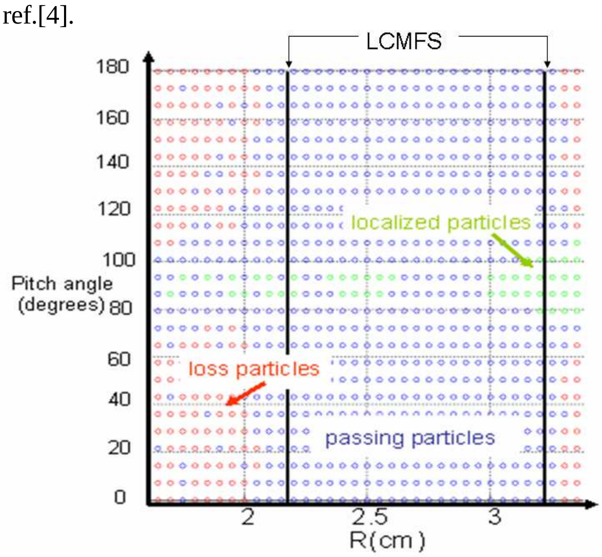

Fig.4 Fast ion confinement diagram of TOKASTAR

4. Proposal of improved TOKASTAR

We showed in Sec.3 that C-TOKASTAR has a low vacuum rotational transform. In order to raise rotational transform we propose improved TOKASTAR which has helical component in the inner side of this system as shown in Fig.5. In this figure, we define ha and hb as outer helical radius and inner helical radius, respectively.

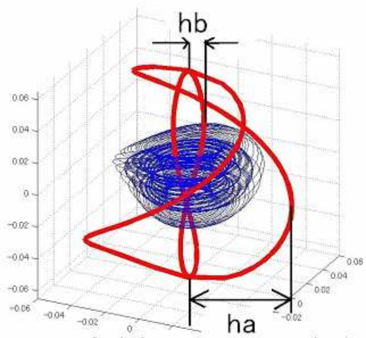

Fig.5 Improved TOKASTAR with inner helical coil

We clarify that with increase in the ratio hb/ha, the vacuum rotational transform improves (Fig.6). When hb/ha is 0.14, the rotational transform becomes ~0.1. But, with the increase in hb/ha, the plasma volume becomes smaller. When hb/ha is 0.14, the plasma small radius of improved TOKASTAR is 1/3 as large as that of TOKASTAR.

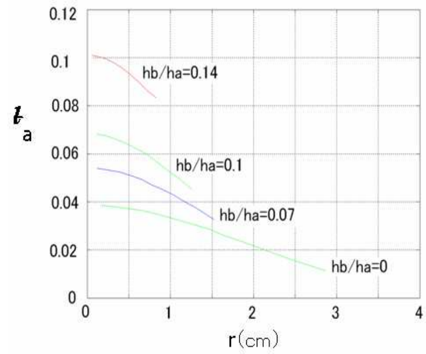

Fig. 6 Rotational transform in the improved TOKASTAR with central helical coil modification

Generally, when average vacuum rotational transform increases, the deviation Δ between fast ions orbit and magnetic surface will decrease and, fast ions confinement can be improved. We confirm its relationship between the rotational transform and the shift Δ (Fig.7). In Table 1, we show the effect of inner helical modifications on rotational transform increase and loss particle reduction in improved TOKASTAR systems. In Fig.7, as the vacuum rotational transform increase, 2Δ/2a, ratio of the orbit shift Δ and the plasma small radius a, is decrease. When the vacuum rotational transform is 0.092, the shift Δ becomes nearly zero. As shown in Table 1, the increase in vacuum rotational transform leads to the improvement of fast ions confinement. When hb/ha is 0.14, a ratio of loss particles is about 8.3%.

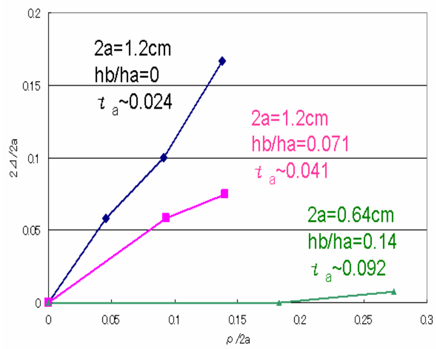

Fig.7 Average rotational transform as a function

Secondly, we proposed improved TOKASTAR(3) which reduces magnetic ripple on the outer side of TOKASTAR system. As shown in Fig.8, a large outer

Table 1 A ratio of loss particle in improved TOKASTAR

	hb/ha	vacuum rotational transform	ratio of loss particles
TOKASTAR	0	0.024	0.133
Improved TOKASTAR #1	0.071	0.041	0.127
Improved TOKASTAR #2	0.14	0.092	0.083

coil system is adopted for this analysis. We move helical component away from plasma, and magnetic ripple σ decreases on the outside of this system (left figure of Fig.8). The comparisons between improved #3 and original configurations are as follows;

σ =0.007/0.09=0.078 (improved TOKASTAR #3),
σ =0.76 (original TOKASTAR).

We expected that the outer helical ripple reduction causes improvement of fast ions confinement, but the ratio of loss particles increase (66.1%). It is because when we reduce helical ripple component, vacuum rotational transform decreases at the same time. So the present model #3 is not effective to improve fast particle confinement.

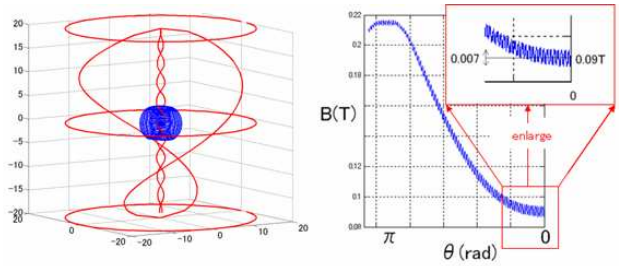

Fig.8 Improved model #3 (left), and its magnetic ripple as a function of θ (left).

Thirdly, we proposed improved TOKASTAR #4 which have 4 helical coils as shown in Fig.9. It has ultra low aspect ratio as

A~2 (improved TOKASTAR #4),
A~2.7 (original TOKASTAR).

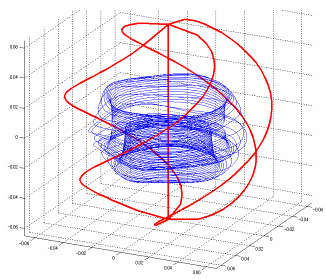

Fig.9 model #4 TOKASTAR with N=4 symmetry.

5. Impedance method in C-TOKASTAR experiments

In order to check the existence of magnetic surface in C-TOKASTAR device, an electron-emission impedance method is used. Table 2 shows parameters of C-TOKASTAR device with double 10-turn helical coils and a pair of 20-turn poloidal coils. As shown in Fig.10, we insert electron gun filament in C-TOKASTAR, and detect the electron current. When the magnetic surface is formed, the electrons go round magnetic surface and go out to the ground finally. So larger circuit impedance can be detected than that when magnetic surface does not exist.

Table 2 Parameters of C-TOKASTAR device

major plasma radius (typical)	35mm
radius of poloidal coil	140mm
radius of spherical helical coil	130mm

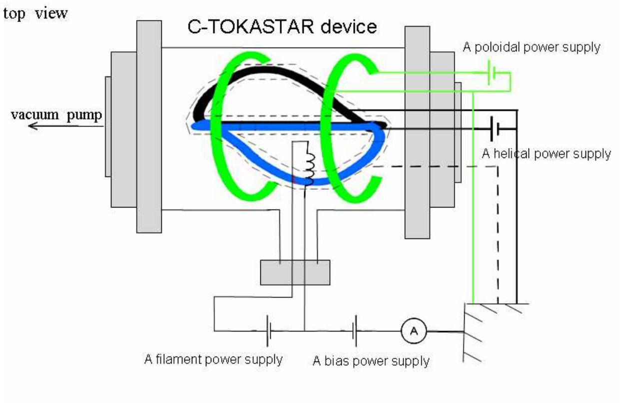

Fig.10 Experimental layout of electron-emission impedance method in C-TOKASTAR

In Fig. 11(a) and (b), we show result of impedance method. In Fig. 11(a), we light an electron gun filament for about 18min, and during that we change helical coil current (H(A/turn)) and poloidal coil current (P(A/turn)). In this experiment a bias power supply voltage is 9.4V. In this figure we also show magnetic surfaces analyzed by HSD. When H/P is 6~10, magnetic surfaces are formed. This result agrees with that analysis.

In Fig.11(b), we first energize helical and poloidal coils and then light an electron gun filament, which turn is reversed from Fig.12. The electrons are emitted for about 30second per shot, and 9 shot results are shown in Fig. 11(b). In this experiment with bias voltage of 19.2V, we confirm an influence of a magnetic field. When H/P is 10, the impedance becomes smallest. By this electron-emission impedance method, we can confirm influence of a magnetic field, and suggest the existence of magnetic surface.

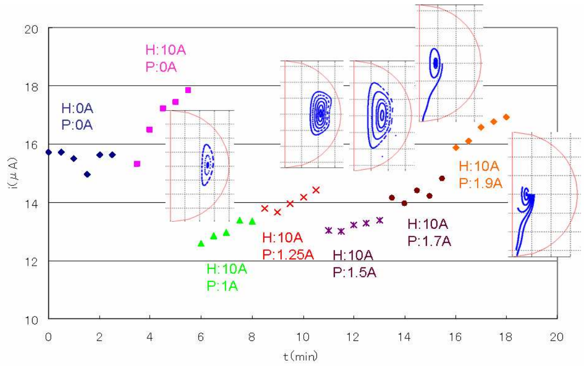

Fig.11(a) Impedance method with quasi-steady electron emission by changing magnetic configuration

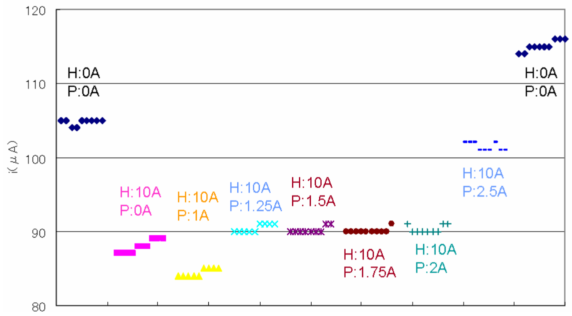

Fig.11(b) Impedance method with short electron emission in quasi-steady magnetic configuration

6. Conclusion

We analyzed fast particle orbit in a compact spherical tokamak-stellarator hybrid TOKASTAR. Several concepts with inner helical coils are proposed to improve particle confinement, and the particle loss reduction in is clarified. A miniature machine C-TOKASTAR was constructed and an electron-emission impedance method is applied for checking magnetic surfaces. We found by comparisons with HSD analysis that magnetic surfaces might be formed in this C-TOKASTAR device

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