Helical-Tokamak Hybridization Concepts for Compact Configuration Exploration and MHD Stabilization

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Abstract. To search for low-aspect-ratio torus systems, a lot of exotic confinement concepts are proposed so far historically. One of the authors previously proposed the tokamak-helical hybrid called TOKASTAR (Tokamak-Stellarator Hybrid) to improve the magnetic local shear near the bad curvature region. This is characterized by simple and compact coil systems with enough divertor space relevant to reactor designs. Based on this TOKASTAR concept, a toroidal mode number $N = 2$ C (compact) -TOKASTAR machine ($R \sim 35$ mm) was constructed. The rotational transform of this compact helical configuration is rather small to confine hot ions, but can be utilized as a compact electron plasma machine for multi-purposes. The C-TOKASTAR has a pair of spherically winding helical coils and a pair of poloidal coils. Existence of magnetic surface and electron confinement property in C-TOKASTAR device were investigated by an electron-emission impedance method. Calculation of the particle orbit also supports that closed magnetic surface is formed in the cases that the ratio between poloidal and helical coil current is appropriate. Another aspect of the research using TOKASTAR configuration includes the evaluation of the effect of the outboard helical field application to tokamak plasmas. It is considered that outboard helical field has roles to assist the initiation of plasma current, to improve MHD stability, and so on. To check these roles, we made TOKASTAR-2 machine ($R \sim 0.12$ m, $B \sim 1$ kG) with ohmic heating central coil, eight toroidal field coils, a pair of vertical field coils and two outboard helical field coil segments. The electron cyclotron heating plasma start-up and plasma current disruption control experiments might be expected in this machine. Calculation of magnetic field line tracing has revealed that magnetic surface can be formed using additional outer helical coils.

1. Introduction

To search for low-aspect-ratio torus systems, a lot of exotic confinement concepts are proposed so far historically [1-7]. Those compact systems sometimes employ the hybridization concept among tokamak, helical, and open field. One of the authors previously proposed the tokamak-helical hybrid called TOKASTAR in 1985 to improve the magnetic local shear near the bad curvature region [8]. This is characterized by simple and compact coil systems with enough divertor space relevant to reactor designs. Moreover, if the plasma current is induced, it will support to increase rotational transform. At first, TOKASTAR having the toroidal period $N = 4$ was proposed, followed by the proposal of $N =$ 1 or *2* simple coil system named "C-TOKASTAR" [9]. An experimental device having $N =$ 2 coils of C-TOKASTAR was constructed and the formation of the vacuum magnetic flux surfaces was confirmed experimentally [10]. Plasma equilibrium with toroidal current was also analyzed in the $N = 2$ TOKASTAR configuration [11]. Based on these achievements, deeper understanding of the relationship among the plasma current, helical magnetic configurations, and confinement property in TOKASTAR configuration is needed. Especially, the research of superposition of the external helical magnetic field to tokamak plasma is important to improve the stability of tokamak plasmas, for example, to suppress plasma current disruption [12,13]. For this purpose, a tokamak-helical hybrid plasma confinement device "TOKASTAR-2" has recently been constructed. First plasma was just produced in June, 2009 [14]. In this paper, we would like to describe the present status of the research of TOKASTAR configuration using C-TOKASTAR and TOKASTAR-2 devices.

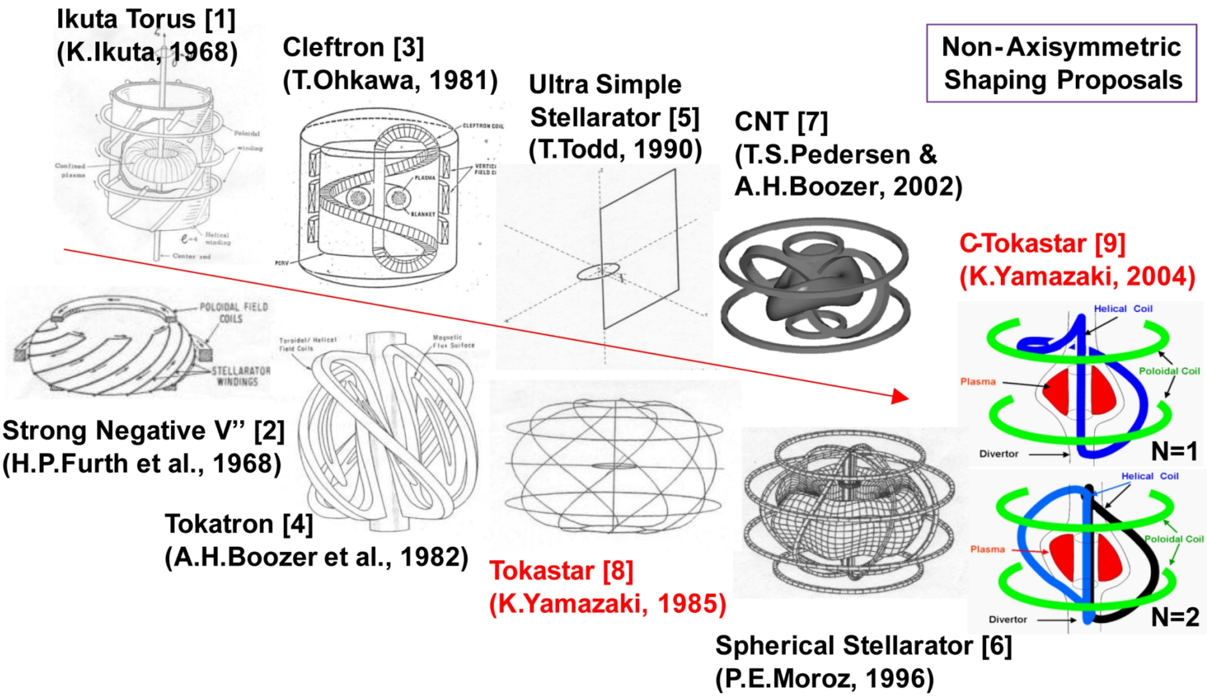

FIG. 1. Proposal of TOKASTAR comparing with other compact helical configurations.

2. C-TOKASTAR Experiment

Figure 2 shows 3-D plasma configuration (left) of N = 2 C-TOKASTAR and poloidal cross-section of flux surfaces with $<\beta> \sim 4$ % analyzed by the VMEC code [15]. Current-free low-beta equilibrium and flux-conserving high-beta equilibrium with plasma current are shown together. The C-TOKASTAR device has double 10-turn helical coils and a pair of 20-turn poloidal coils. Major plasma radius is typically 35mm, radius of poloidal coil is 70mm, and radius of spherical winding frame of helical coil is 65mm. In order to check the existence of magnetic surface and electron confinement property in C-TOKASTAR device, an electron-emission impedance method is used. Figure 3 shows the experimental setup of the electron-emission impedance method in C-TOKASTAR device. In this method, an electron gun filament is inserted into C-TOKASTAR and the electron current is detected. If the magnetic surface is formed, the electrons go around the magnetic surface and finally exit to the ground. Therefore, circuit impedance becomes larger than that in the case without magnetic surfaces, which results in a decrease of the emission current. Figure 4 shows the dependence of the electron emission current of the electron-emission impedance on magnetic configuration. Poloidal cross sections of the particle orbit with the helical coil current I_H = 10 A and the poloidal coil current I_P = 1.0 A, 1.25 A, 1.5 A, 1.7 A, 1.9 A are shown together. A clear decrease in the emission current signal was observed during I_H/I_P = 0.1 to 0.17 compared than the cases with I_H/I_P = 0, 0.19, and I_H = 0 A shown by a blue filled

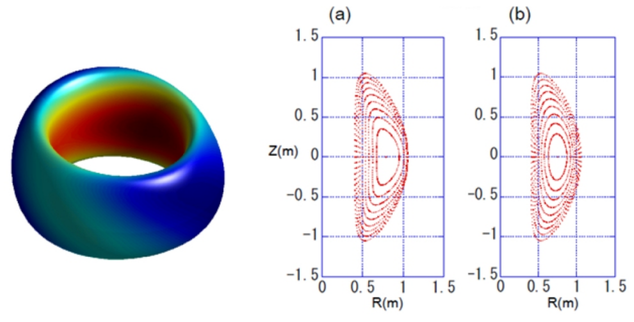

FIG. 2. 3-D plasma configuration (left) of N = 2 C-TOKASTAR and poloidal cross-section of flux surfaces (right) with $<\beta>\sim 4\%$. (a) current-free equilibrium, (b) flux-conserving $<\beta>\sim 8\%$ equilibrium with plasma current.

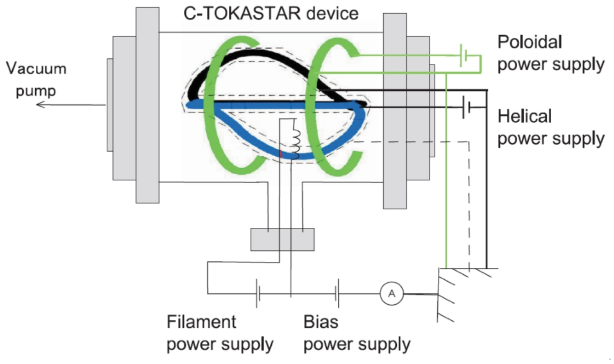

FIG. 3. Experimental setup of the electron-emission impedance method in N = 2 C-TOKASTAR device.

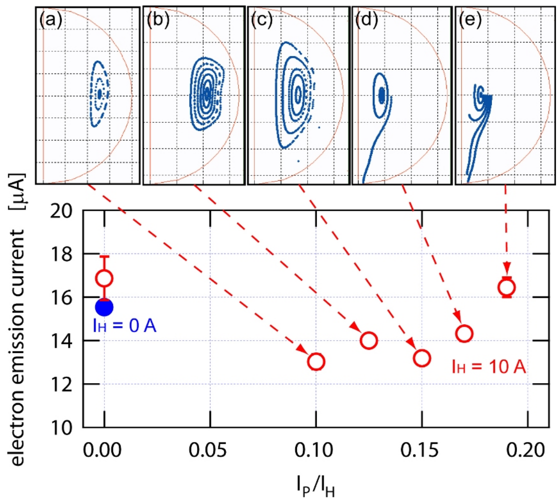

FIG. 4. Dependence of the electron emission current of the electron-emission impedance on magnetic configuration.

circle as a reference. Calculation of the particle orbit also supports that closed magnetic surface is formed in the cases that I_H/I_P is between 0.1 and 0.17. Under the condition of I_H/I_P with the magnetic surface, the signal level which has a correlation with the confinement property of corresponding magnetic surface slightly depends on the I_H/I_P ratio. The relationship between I_H/I_P ratio and the confinement property should be addressed as a future work.

3. TOKASTAR-2 Experiment

3.1. Overview of TOKASTAR-2 Device

Figure 5 shows the coil configurations of TOKASTAR-2 device and magnetic flux surfaces of tokamak operation calculated using TOSCA code [16]. In this calculation of the flux surfaces, the plasma current I_p = 2.5 kA is assumed in tokamak operation. The major radius R_p and the averaged minor radius $\langle a_p \rangle$ of the toroidal plasma with nearly circular cross-section is expected to be approximately 0.1 m and 0.04 m, respectively. TOKASTAR-2 has ohmic heating (OH) central coils, eight toroidal field (TF) coils and two outboard helical field (HF) coil segments. Each coil consists of cupper conductor with a diameter of 3.2 mm. There are 50 turns in TF coil, 100 turns in vertical field (VF) coil, 42 turns × 2 layers in the central part of OH coil, 22 turns in upper and bottom part of OH coil, and 98 turns in HF coil. These coils are installed in the vacuum cryostat except external VF coils. At maximum three units of 5 kV 200 μF capacitors are used for the power supply to coils. Helium or Hydrogen is used for the working gas. Base pressure of the vessel is in the

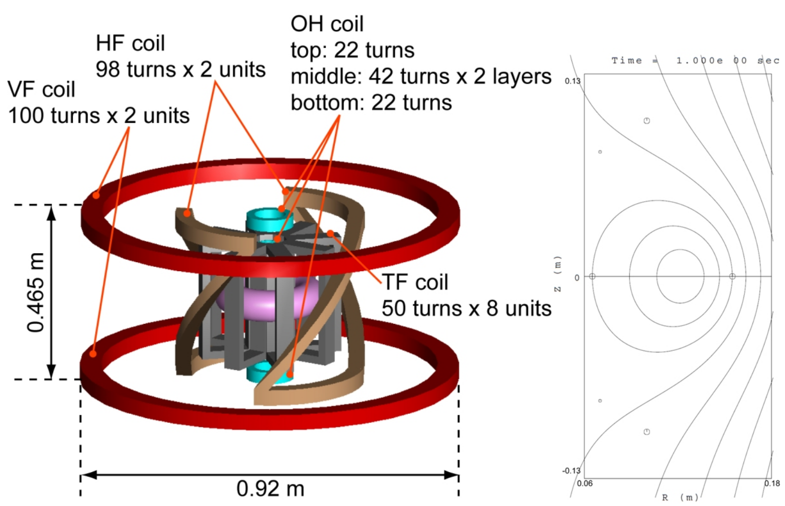

FIG. 5. Coil configuration of TOKASTAR-2 device and magnetic flux surfaces of tokamak operation calculated using TOSCA code.

order of 10^{-3} Pa. Experiment region of the gas pressure is 0.4 – 7.0 Pa when helium is the working gas. A radiofrequency (RF) wave with the frequency of 2.45 GHz and the injected power up to 2.0 kW is used for the start-up of the plasma.

3.2. Production of ECH Plasmas as a Pre-ionized Phase of the Tokamak Operation

The electron cyclotron heating (ECH) plasma start-up experiment using the RF wave is in progress in this machine. Figure 6 shows the typical waveform of the ECH plasma discharge. The toroidal magnetic fields B_t calculated using the TF coil current and the visible optical emission intensity measured using an avalanche photodiode detector (APD) are shown together. RF wave with the power of 0.4 kW was injected continuously. As shown in this figure, the onset of the APD signal corresponds to the time that B_t in the innermost region of the volume inside the TF coils (major radius R = 0.06 m) reaches to 0.0875 T which is the electron cyclotron resonance (ECR) field for 2.45 GHz RF. The APD signal starts to decrease when B_t becomes lower than the ECR field. These facts suggest that plasmas are produced by ECR.

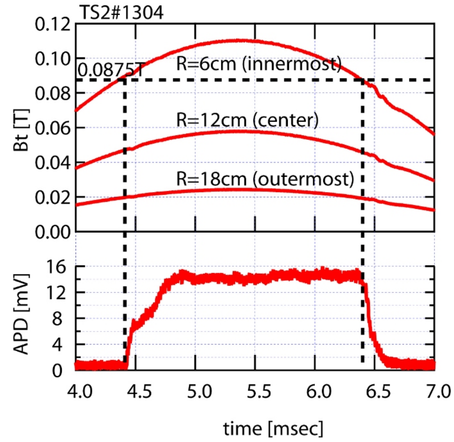

FIG. 6. Temporal evolutions of the toroidal field strength at three locations calculated using the TF coil current (upper) and the intensity of visible emission measured using the avalanche photodiode detector (lower).

We have a plan to induce plasma current in this ECH plasma. The ECH discharge corresponds to the "pre-ionized phase" of the tokamak operation. The mechanism of initiation and heating of the pre-ionized plasmas should be clarified. In addition, as another objective to study the ECH plasma, if there are radial electric fields in the ECH plasmas, closed surfaces of the particle orbit could be formed by $E\times B$ drift. There is a possibility that outer helical magnetic fields assist to form the closed surface. Based on these motivations, we are conducting the measurement of parameters of this ECH plasma. Figure 7 shows the radial profiles of electron density and temperature of the ECH plasma measured using Langmuir probes. In this experiment, the electron density and temperature was in the order of 10^{16} m^{-3} and 10 eV, respectively. The radial position of the peak value is close to the position of the upper hybrid resonance (UHR) layer rather than that of the 1st or 2nd ECR layer. Therefore, we suspect that the plasma is initiated by the ECR as described above and further heated by the UHR. Figure 8 shows the radial profile of the ion saturation currents I_{is} and the floating potentials V_f of the ECH plasma. Each profile was measured using

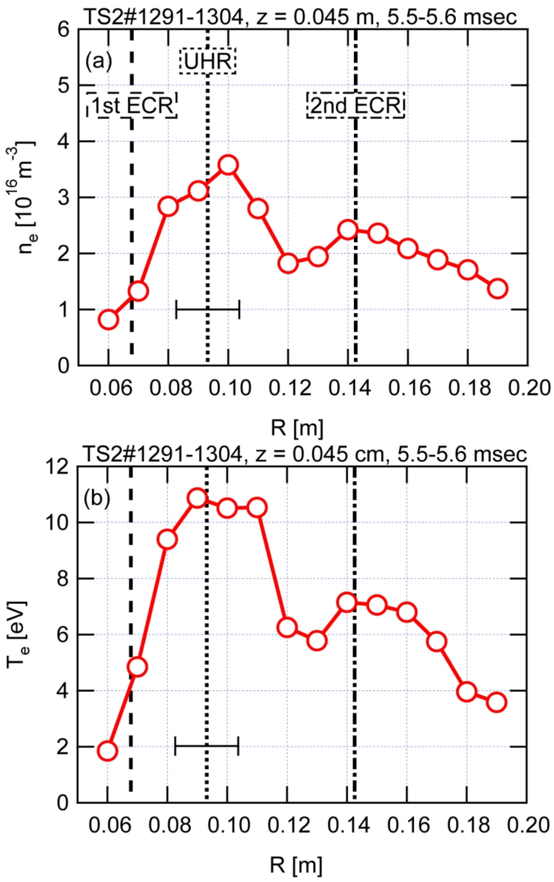

FIG. 7. Radial profiles of (a) electron density and (b) electron temperature of the ECH plasma as the pre-ionized phase of tokamak operation.

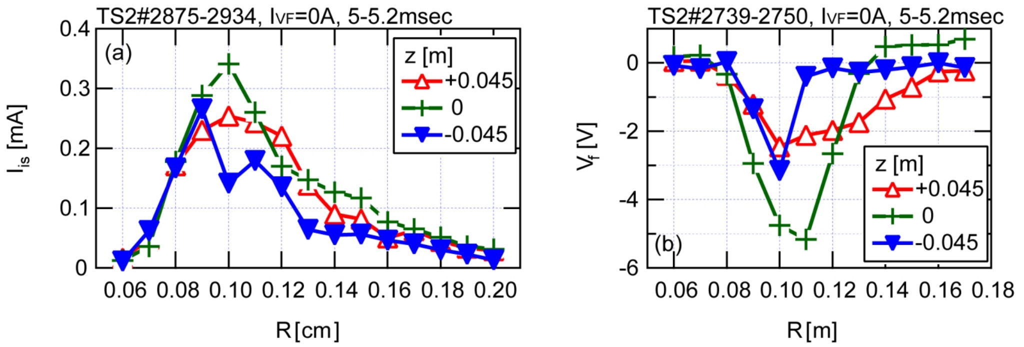

FIG. 8. Radial profiles of (a) ion saturation currents and (b) floating potentials measured using Langmuir probes at z = +0.045, 0, -0.045 m. The midplane corresponds to z = 0 m.

Langmuir probes located at three vertical position z = +0.045 m, 0 m, and -0.045m, where the midplane corresponds to z = 0 m. As shown in this figure, both I_{is} and V_f have peak values around R = 0.1 m radially and z = 0 m vertically.

We are trying to induce plasma currents using Ohmic heating as a next step. It has been confirmed that the plasma current increases after the onset of the current in the OH coil. However, the current reaches up to only several tens of amperes at maximum. It has to be much improved to generate the sufficient rotational transform of the magnetic field. Plans to increase the plasma current include upgrading power supply circuit to increase the loop voltage, optimization of the vertical field by equilibrium calculation, and evaluation of eddy currents in the vessel.

3.3. Suppression of Fluctuations by Applying the Outer Magnetic Fields

Physics of the fluctuation of plasma parameters is important because it is considered to be correlated with the plasma confinement. The characteristic of fluctuations was compared between with and without the vertical magnetic field in Fig. 9. Figure 9(a) shows that large fluctuation exists in the I_{is} of the ECH plasma only when the vertical field is not imposed. The frequency spectrum of the fluctuation is shown in Fig. 9(b). Fluctuation having frequencies of less than 100 kHz is dominant. Figure 9(c) shows the radial profile of the fluctuation level evaluated using the standard deviations of the signals divided by the DC values. The peak value of the fluctuation level is located around R = 0.13 m, although the peak location of the profile of I_{is} itself is around R = 0.1 m. One can see that the fluctuation is almost completely suppressed when the vertical field

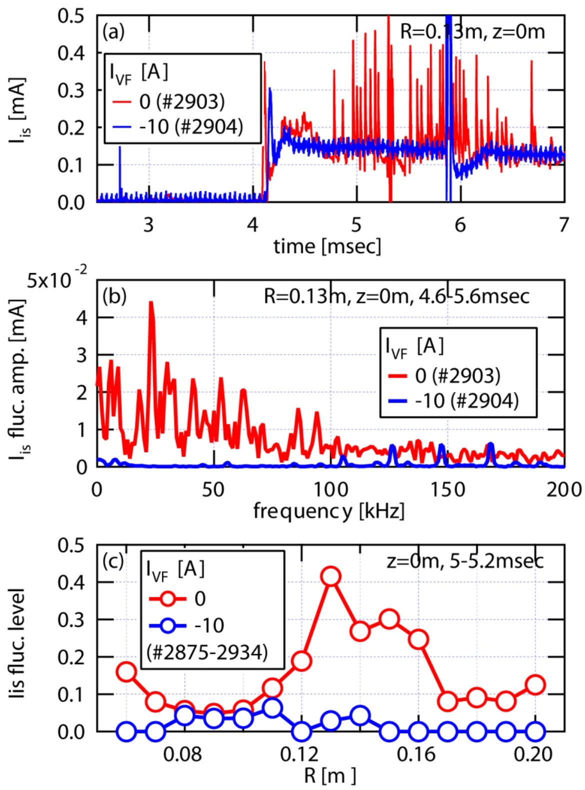

FIG. 9. (a) Temporal evolution and (b) frequency spectrum of the ion saturation current at the location where the fluctuation is largest in the ECH pre-ionized plasma. (c) Radial profile of the fluctuation level evaluated using the standard deviations of the signals divided by the DC values.

was imposed. Note that several peaks having frequencies of larger than 100 kHz in the frequency spectrum in Fig. 9(b) are identical to those in the noise. In addition, fluctuations in the ECH plasmas were suppressed by applying not only the vertical field but also the helical field.

Physics of the growth and suppression of fluctuation has not been clarified yet. We have several hypothesis of the reason to suppress fluctuations as follows. One is that the error magnetic field might be corrected by the outer magnetic fields. The other is that the orbit of magnetic field lines or particle motions might be modified, and it results in the reduction of plasma-material interaction. To investigate these effects, magnetic field line tracing analysis including the vertical field or the helical field is considered as a future plan.

3.4. Formation of vacuum magnetic flux surface by applying outer helical field

Another objective of the study is to check the probability of formation of vacuum magnetic surface by applying helical fields. Therefore, magnetic field tracing code HSD (helical system design) [16] is used to investigate whether vacuum magnetic surfaces can be formed or not in TOKASTAR-2. Magnetic field lines can be calculated in this code by defining coil configuration and currents in each coil as input parameters. This calculation of tracing magnetic line has revealed that the vacuum magnetic surface can be formed by using additional sector coil to simulate C-TOKASTAR configuration. Figure 10(a) shows the configuration of the additional sector coils for the formation of vacuum magnetic surface without plasma current. In this case, the position of the additional sector coil is 0.01 m separated from the original helical coils vertically. Last closed flux surface (LCFS) having vertically elongated shape formed using the additional sector coils are shown together in Figure 10(a). The current in TF coil (I_{TF}), VF coil (I_{VF}), HF coil (I_{HF}), and additional sector coil (I_{AS}) was 6250 AT, 28800 AT, 6250 AT, and 6625 AT, respectively. Note that all magnetic field lines are shown in the projected side view (R-z) and this is not a normal Poincare-plot. Figure 10(b)(c) shows the radial profile of the averaged rotational transform

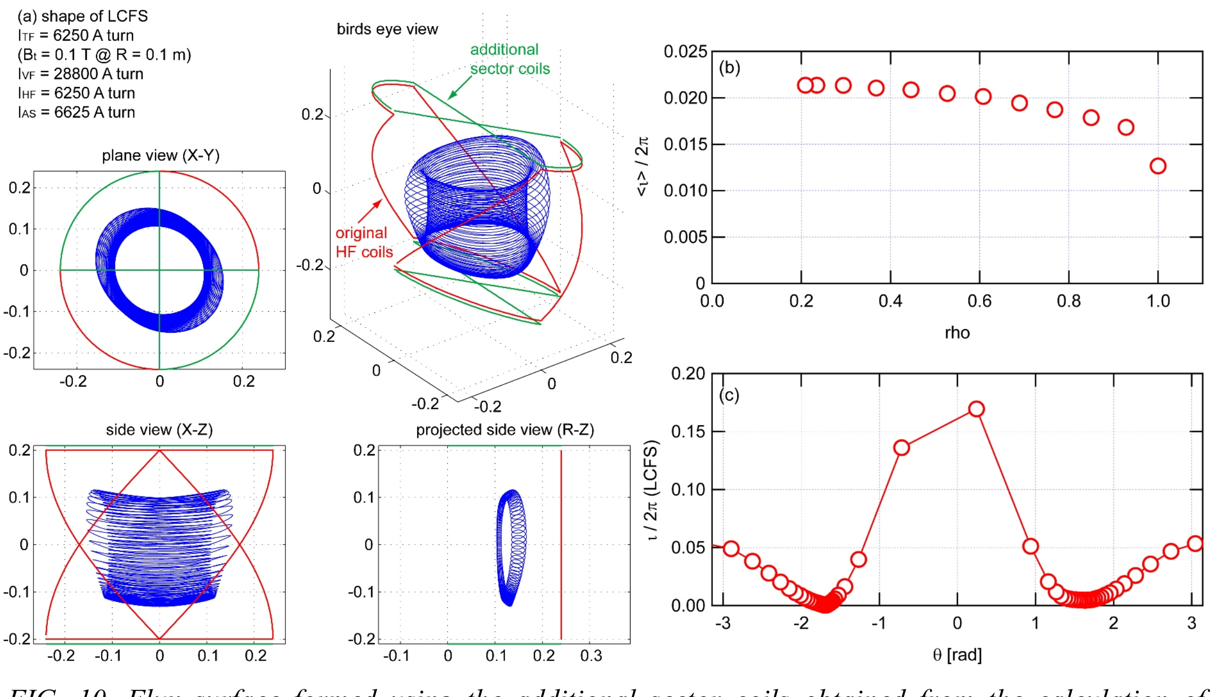

FIG. 10. Flux surface formed using the additional sector coils obtained from the calculation of magnetic field line tracing. (a) Shape of the last closed flux surface (LCFS), (b) radial profile of the averaged rotational transform, and (c) poloidal profile of the rotational transform of LCFS.

and the poloidal profile of the local rotational transform, respectively. The maximum value of the local rotational transform is located around poloidal angle $\theta = 0$, which corresponds to the outboard on the midplane.

The peaked rotational transform is rather strong, but the averaged value obtained in this calculation might be insufficient for the stable confinement of plasmas. However, it could help the ramp-up of the plasma current by forming the flux surfaces to trap plasmas tentatively before the induction of the plasma current. Optimization of such current ramp-up scenarios should be investigated for the future. Characteristics of the magnetic surface, such as size, rotational transform or magnetic well depend on the amount and the ratio of currents in each coil, which should be investigated to evaluate the property of plasma confinement.

3.5. Plasma current assisted TOKASTAR configuration

In order to raise the averaged rotational transform in TOKASTAR configuration, several analyses have been carried out. One is to add inboard-side helical coil perturbations. By scarifying the merit of low aspect ratio, we confirmed theoretically that the plasma equilibrium, stability and particle confinement are improved [10,11]. Another approach is to carry plasma current. As shown in Fig. 11, by the magnetic bumpy components are relaxed and the averaged rotational transform is raised. The further optimization of the spherical TOKASTAR configuration is under investigation.

4. Summary

We proposed the tokamak-helical hybrid magnetic field configuration called "TOKASTAR" for compact and low-cost designs of magnetically-confined torus fusion reactors. Based on this TOKASTAR concept, a toroidal mode number N = 2 "C –TOKASTAR" machine was constructed. Existence of magnetic surface and electron confinement property in C-TOKASTAR device were investigated by an electron-emission impedance method. To investigate the relationship between plasma current and outboard helical magnetic fields in TOKASTAR configuration, new torus plasma confinement device "TOKASTAR-2" was constructed. It can impose outer helical field to tokamak plasma by using a pair of helical coils located outside toroidal coils and along the toroidal direction. It was confirmed that pre-ionized plasma for the tokamak operation is produced by the electron cyclotron resonance. Pre-ionized ECH plasma has profiles of the ion saturation current and the floating potential with a peak at the center in both radial and vertical direction. The outer vertical or helical magnetic field application suppresses bursting density fluctuation in the pre-ionized ECH plasmas. Induction of the plasma current by Ohmic heating has to be further improved to realize stable tokamak confinement and to investigate the effect of the outboard helical field on tokamak plasmas. Calculation of magnetic field line tracing has

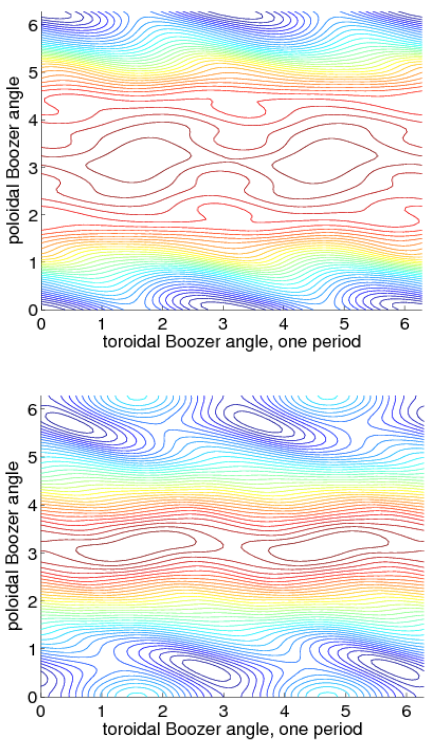

FIG.11. Mod-B contours in the Boozer coordinates near the plasma edge without (upper) and with (lower) plasma current.

revealed that magnetic surface can be formed using additional sector coils. Characteristics of the magnetic surface for plasma confinement should be investigated in the future.

Acknowledgments

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