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Initial experimental results and magnetic surface analysis of tokamak-helical hybrid plasma confinement device "TOKASTAR-2"

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New torus plasma confinement device having tokamak-helical hybrid magnetic configuration “TOKASTAR-2” was constructed. Purposes of study are investigation on the effect of outer helical field on the tokamak plasma and consideration on formation of vacuum magnetic surface applying helical field. We confirmed that pre-ionized plasma of the tokamak operation is produced using the electron cyclotron resonance heating. Calculation of magnetic field line has revealed that magnetic surface can be formed using additional outer helical coils, even if plasma current is not induced.

Keywords: tokastar, tokamak, helical, equilibrium, hybrid confinement, compact torus, magnetic surface

1. Introduction

In the research of confinement of torus plasma using magnetic fields, a concept of superposition of the external helical magnetic field to tokamak plasma has been widely proposed. One of the objectives of this concept is to improve the stability of plasmas, for example, to suppress plasma current disruption [1, 2].

A tokamak-helical hybrid plasma confinement device "TOKASTAR-2" has recently been constructed to investigate the effect of helical field to tokamak plasma. The name of TOKASTAR means the abbreviation of tokamak and stellarator [3]. A first plasma was just produced in June, 2009. Purposes of the study using TOKASTAR-2 are as follows:

- investigation on the effect of outer helical fields on tokamak plasmas.
- consideration on formation of vacuum magnetic surface applying outer helical fields.

In this paper, characteristics of newly constructed TOKASTAR-2 device and present states of the study for the purpose described above. In chapter 2, overview of TOKASTAR-2 device and calculation of toroidal magnetic field are described. Thereafter, experiment to produce pre-ionized plasma of tokamak operation and trial for current induction using ohmic heating coil are shown in chapter 3. At last, consideration on the formation of vacuum magnetic surface without plasma current by modifying the shape of coils is discussed.

2. TOKASTAR-2 Device

Figure 1 is the photograph of experimental setup of TOKASTAR-2 device. Radio frequency (RF) wave

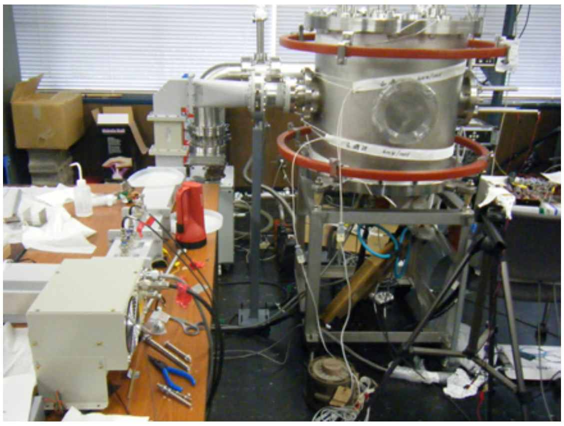

Fig.1 Photograph of the experimental setup of TOKASTAR-2 device. Left: source of 2.45 GHz radio frequency wave, right: vacuum vessel.

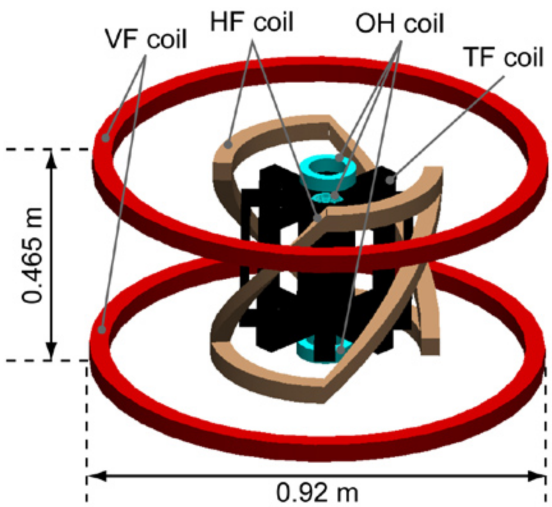

Fig.2 Coil configuration of TOKASTAR-2.

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having the frequency of 2.45 GHz is used to produce plasma by the electron cyclotron resonance (ECR) heating. The injected power of RF wave is 2.0 kW at maximum. Base pressure in the vacuum vessel is in the order of 10^{-3} Pa. He or H_2 gas is introduced in the vessel as the working gas. Present experiment region of gas pressure is 0.4 ~ 7 Pa. Figure 2 shows the coil configuration of TOKASTAR-2. Tokamak plasma is produced using the eight toroidal field (TF) coils, ohmic heating (OH) coils separated to three parts (top, central, bottom), and a pair of vertical field (VF) coils. The toroidal field at the center of the TF coil (R = 0.12 m) is 0.1 T at maximum. External helical field can be applied using the outer helical field (HF) coils of the toroidal period n = 2 or 1. TF, VF, OH coils are located inside vessel. Each coil consists of cupper conductor with a diameter of 3.2 mm. There are 50 turns in TF coil, 100 turns in 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. Several 200 μF capacitors are utilized to energize pulsed current to each coil. The major radius R_p and the averaged minor radius $<a_p>$ of the toroidal plasma with nearly circular cross-section is expected to be approximately 0.1 m and 0.04 m, respectively. Plasma parameters measured using Langmuir probes and Rogowski coil are electron density n_e ~ 10^{16} m^{-3}, electron temperature T_e ~ 10 eV, and plasma current I_p ~ 10 A.

The toroidal magnetic field produced by the TF coils was calculated using Biot-Savart law. Figure 3 shows contour plot of toroidal field produced by toroidal field coils. In this case, the current in a TF coil I_{TF} is 80 A × 50 turns = 4000 AT. ECR layer (B_t = 0.0875 T for the RF frequency = 2.45 GHz) appears in the high field side. However, radial profiles of the toroidal field differ between at toroidal angle ϕ of 0 rad (just inside TF coil) and $\pi/8$ rad (between TF coils). Figure 4(a) is the comparison of the radial profile of the toroidal field in the midplane at $\phi = 0$ rad and $\phi = \pi/8$ rad shown together with analytical solution of averaged toroidal field $B_t = \mu_0 N I_{TF}/2\pi R$, where N is the number of toroidal period (= 8). Difference of the toroidal fields between these two toroidal angle increases near the TF coils, namely, toroidal ripple δ defined by $\delta(R, z) = (B_{max}(R, z) - B_{min}(R, z))/(B_{max}(R, z) + B_{min}(R, z))$ [4] as a function of major radius and vertical position increases near the TF coils as shown in Fig. 4(b). This calculation has revealed that the minimum value of the toroidal ripple

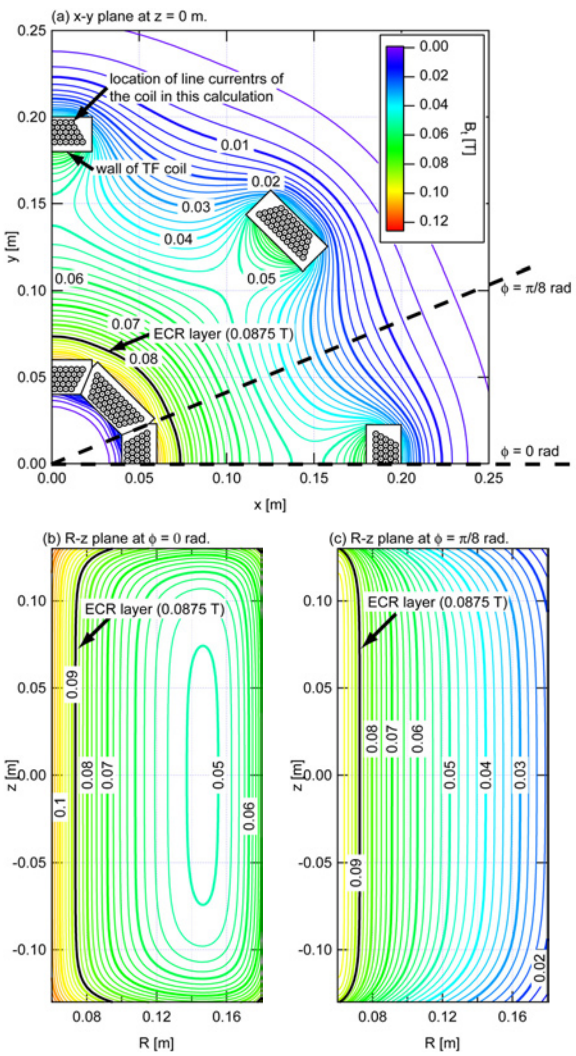

Fig.3 Contour plot of toroidal field produced by toroidal field coils. (a) Top view at the midplane. (b)(c) R-z plane at toroidal angle of 0 rad (just inside TF coil) and π/8 rad (between TF coils), respectively.

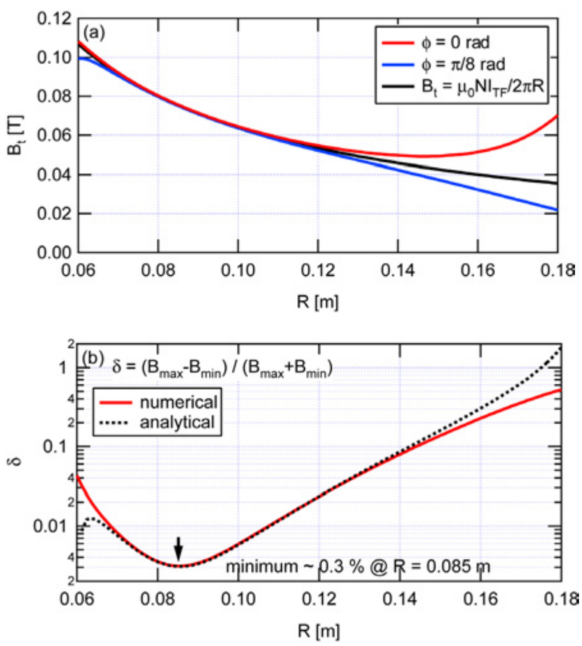

Fig.4 (a) Radial profile of the toroidal field in the midplane at $\phi = 0$ rad and $\phi = \pi/8$ rad shown together with analytical solution of $B_t = \mu_0 N I_{TF}/2\pi R$. (b) Toroidal ripple defined by $(B_{max} - B_{min})/(B_{max} + B_{min})$.

is about 0.3 %, which is evaluated at around R = 0.085 m. In this figure, the profile of toroidal ripple obtained from the analytical solution of the toroidal field is shown together. It is defined by the position of fifty coil filaments located in the wall of TF coil as shown in Fig. 3(a) and following equations,

$$B_t(R,\phi) = \mu_0 N I_{TF} / 2\pi R(1 + f_1 + f_2)$$
$$f_1 = \sum_j \varepsilon_{1j} / \left((R/R_{1j})^N - 1\right)\cos\left(N(\phi + \Delta\phi_{1j})\right)$$
$$f_2 = \sum_j \varepsilon_{2j} / \left((R_{2j}/R)^N - 1\right)\cos\left(N(\phi + \Delta\phi_{2j})\right), \quad (1)$$

where suffix 1 and 2 indicates the inner and outer TF coil, respectively, suffix j (= 1~50) corresponds each coil filament, ε is a weight of summation (= 1/50), $\Delta\phi$ is a toroidal angle of each coil filament. As shown in Fig. 4(b), the minimum value of the toroidal ripple and the location having minimum toroidal ripple have good agreement between calculated and analytical value.

3. Tokamak operation and its pre-ionized phase

One of the purposes of study using TOKASTAR-2 is the investigation of the effect of outer helical field to tokamak plasma. We have a plan to induce plasma current in plasmas produced using the ECR heating. This ECR plasma is called "pre-ionized phase" of the tokamak operation. However, it is not trivial that plasmas are initiated by ECR because the RF wave might be reflected randomly in a small and non-torus vessel like this device and there is a possibility that it is not absorbed correctly at ECR layer. To confirm whether pre-ionized ECR plasma can be produced or not, plasma parameters were measured at the position where ECR layer appears. Figure 5 shows temporal evolution of toroidal field and ion saturation current measured using Langmuir double probe. Both values are measured or calculated at major radius R = 0.07 m and height from the midplane z = 0.045 m. Three cases with different voltage charged for a current discharge to TF coils are compared. RF was injected continuously during the period shown in the figures. Time that the toroidal magnetic field B_t reaches to the ECR field can be varied with scanning a charged voltage to the capacitor for the discharge to TF coils. One can see that the onset of the probe signals corresponds to the time that B_t reaches to the ECR field. After the onset of discharge, the probe signal vanishes because the peak of density profile moves to the low field side. At the last of discharge, probe signals appear again at the time that toroidal field become close to the ECR field. These facts suggest that plasma was produced by ECR. Investigation on the pre-ionized plasma has another purpose as a preliminary examination for the operation using the magnetic surfaces without inductive plasma current. In this case, it is desirable to adjust the position of initiation of plasma to the position of the magnetic surface. Formation of the magnetic surfaces without plasma current will be described in the next section.

Now we are trying to induce the plasma current in the ECR pre-ionized plasma described above. Figure 6 shows the typical waveform of tokamak operation. Toroidal field, current in OH coil, power of RF, plasma current intensity of optical emission are shown together. RF having the power of 0.25 kW was injected continuously. Current in the VF coil was 2000 AT. The plasma current increases after the onset of the current in the OH coil. It reaches up to 25 A in this shot. However, it has to be much improved to generate the sufficient rotational transform of the magnetic field. We roughly estimated available toroidal current from the loop

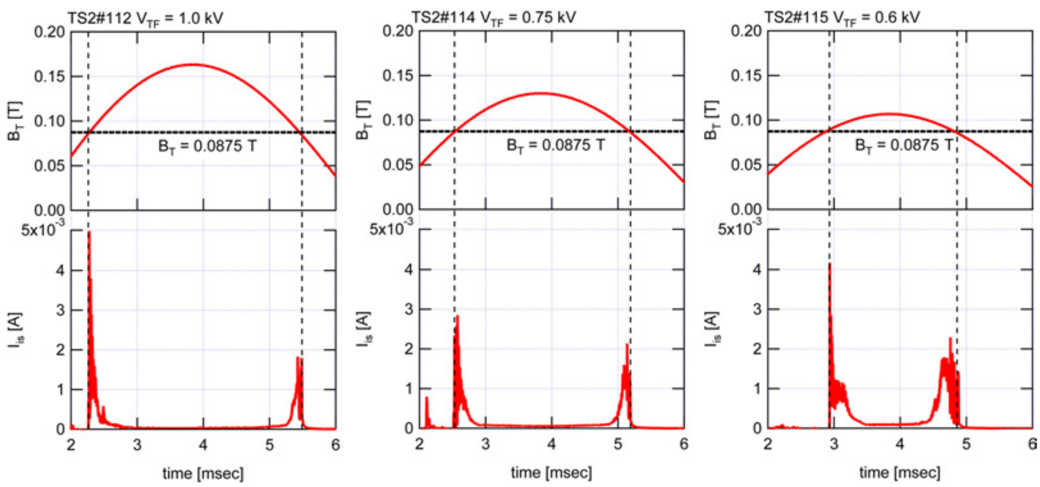

Fig.5 Temporal evolution of toroidal field and ion saturation current measured using Langmuir double probe. Both values are measured at major radius R = 0.07m and height from the midplane z = 0.045 m. Three cases with different voltage charged for a current discharge to TF coils are compared.

voltage and Spitzer resistivity deduced from electron temperature. T_e measured using the Langmuir probe is about 10 eV. Then, Spitzer resistivity $\eta = (N(Z)\ Z)\ 1.65 \times 10^{-9} \ln\Lambda / T_e^{3/2} = 4.8 \times 10^{-5}$ Ωm, where ion charge $Z = 2$ and coefficient $N(Z) = 0.85$ for helium plasmas, and Coulomb logarithm $\ln\Lambda = 17$. If we assume the shape of torus plasma having the major radius R = 0.1 m and minor radius a = 0.04 m, the resistance $R_p = \eta \times 2\pi R / \pi a^2 = 6.0 \times 10^{-3}$ Ω. The maximum loop voltage V_{loop} in this device is about 8 V. Therefore, expected plasma current $I_p = V_{loop} / R_p$ = 1.3 kA. It is about fifty times larger than the value obtained at present. Now we have plans to increase the loop voltage by upgrading power supply circuit and optimize the vertical field by equilibrium calculation to increase I_p. If I_p can be increased by a hundred times compared than that in the present status, the safety factor $q = aB_t / RB_p$ will be approximately 3 for B_t = 0.1 T.

4. Formation of magnetic flux surface by applying outer helical field

Another objective of the study is consideration on probability of formation of magnetic surface by applying helical fields. Therefore, magnetic field tracing code HSD (helical system design) [5] is used to investigate whether vacuum magnetic surfaces can be formed or not in TOKASTAR-2. Magnet 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 helical coil. Figure 7 shows the configuration of the additional helical coils for the formation of vacuum magnetic surface without plasma current. Last closed

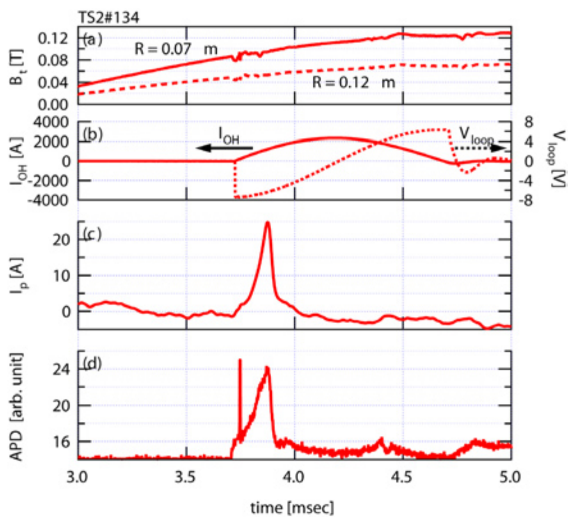

Fig.6 Waveform of tokamak operation. (a) Toroidal field, (b) current in OH coil and loop voltage, (c) plasma current and (d) intensity of optical emission.

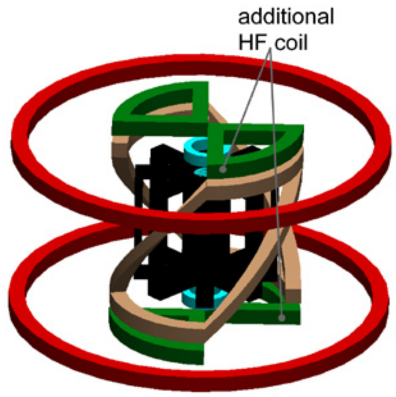

Fig.7 Additional helical coil for the formation of vacuum magnetic surface without plasma current.

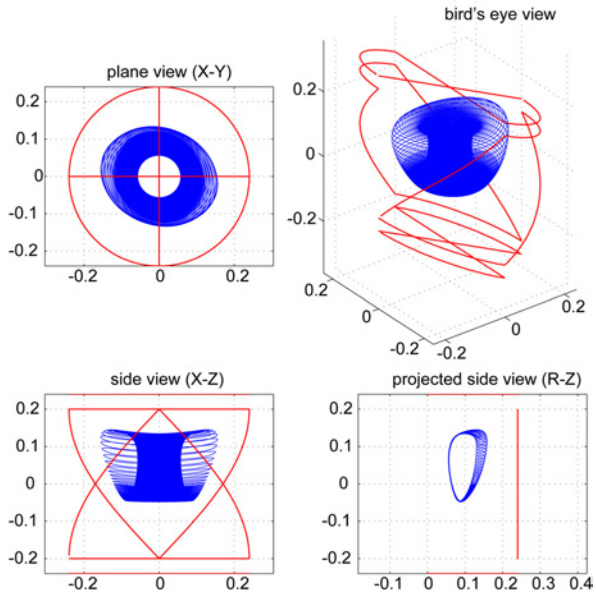

Fig.8 Last closed flux surface formed using the additional helical coils obtained from the calculation of magnetic field line tracing. I_{TF} = 6250 AT, I_{VF} = 15218 AT, I_{HF} = 6250 AT, $I_{H'F}$ = 7500 AT.

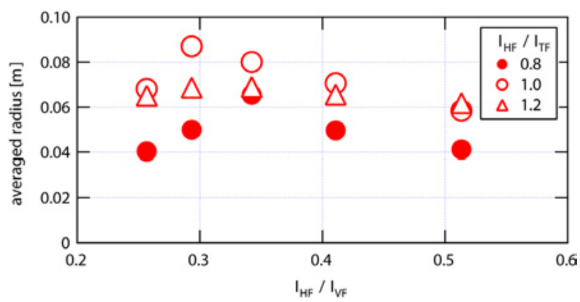

Fig.9 Averaged plasma minor radius as a function of a ratio I_{HF}/I_{VF} in several cases of I_{HF}/I_{TF}.

flux surface (LCFS) having vertically elongated shape formed using the additional helical coils are shown in Fig. 8. In this case, current in TF coil (I_{TF}), VF coil (I_{VF}), HF coil (I_{HF}), and additional helical coil ($I_{H'F}$) was 6250 AT, 15218 AT, 6250 AT, and 7500 AT, respectively. Note that all the Poincare-plot points are projected in the projected side view (R-z) and it does not mean that the flux surface has finite width.

The shape of the magnetic surface varies with the ratio between I_{TF}, I_{VF}, I_{HF}, and $I_{H'F}$. In this paper, we regard the averaged minor radius $\langle r \rangle$ defined by $\langle r \rangle = (a \times b)^{1/2}$, where a and b is short and long radius of LCFS, respectively, as an indicator of the size of LCFS. Figure 9 show a dependency of $\langle r \rangle$ on the ratio I_{HF} / I_{VF}. In this figure, results in several cases of I_{HF} / I_{TF} are plotted together. The ratio $I_{H'F} / I_{HF}$ was fixed to be 1.2 in all cases. It has been revealed that $I_{HF} / I_{VF} = 0.3 \sim 0.35$ is an optimized ratio to enlarge the cross section.

As a next step, detailed analysis on the characteristics of the magnetic field structure, such as rotational transform or magnetic well, will be needed to evaluate the property of plasma confinement.

5. Summary

New torus plasma confinement device having tokamak-helical hybrid magnetic configuration "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. We confirmed that pre-ionized plasma of the tokamak operation is produced using the electron cyclotron resonance heating. Ohmic heating was applied to induce plasma current. However, it has to be further improved to realize stable tokamak confinement. Calculation of magnetic field line tracing has revealed that magnetic surface can be formed using modified outer helical coils. Characteristics of the magnetic surface for plasma confinement should be investigated in the future.

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