Construction of a plasma confinement device TOKASTAR-2 with tokamak-helical hybridization concepts

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Abstract. 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. A tokamak-helical hybrid plasma confinement device TOKASTAR-2 has recently been constructed to investigate the effect of helical field to tokamak plasma. First plasma was just produced in June, 2009. TOKASTAR-2 machine has Ohmic heating central coils, eight toroidal field coils and two outboard helical field coil segments. 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. The toroidal magnetic field $B_t$ is typically 0.1 T. The plasma start-up experiment using the electron cyclotron heating (ECH) by the radio frequency wave with the frequency of 2.45 GHz and the injected power of 2.0 kW is in progress in this machine as the pre-ionized phase of tokamak operation. In this paper, the overview of TOKASTAR-2 device and present states of the study are presented. According to the preliminary experiment, we confirmed the effect of outer vertical or helical magnetic field application to suppress bursting density fluctuation in the pre-ionized ECH plasmas.

1. Introduction
Many low-aspect-ratio torus systems have been proposed for compact and low-cost designs of fusion reactors [1-7]. Those compact systems sometimes employ the hybridization concept among tokamak, helical, and open field. One of the authors (K. Y.) also proposed the tokamak-stellarator hybrid called TOKASTAR [8]. In TOKASTAR configurations, the flux surface can be formed by simple coils. 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 plasma current was also analysed 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. In this paper, we would like to describe the overview of TOKASTAR-2 device and the present status of the research.

2. TOKASTAR-2 device

Figure 1 shows the coil configurations of TOKASTAR-2 device. It has ohmic heating (OH) central coils, eight toroidal field (TF) coils and two outboard helical field (HF) coil segments. Each coil consists of copper 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 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 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.

![Figure 1. Coils of TOKASTAR-2 device.](image)

3. Production of ECH plasmas as a pre-ionized phase of the tokamak operation

The ECH plasma start-up experiment using the RF wave is in progress in this machine. Figure 2 shows the typical waveform of the electron cyclotron heating (ECH) plasma discharge. The toroidal magnetic fields $B_t$ calculated using the current in the TF coils and the intensity of the visible optical emission 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 $R = 6$ cm) 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. In this experiment, the electron temperature and density was in the order of 10 eV and $10^{16}$ m^{-3}, respectively.

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 3 shows the radial profile of the ion saturation currents $I_s$ and the floating potentials $V_f$ of the
ECH plasma. Each profile was measured using Langmuir probes located at three vertical positions $z = +4.5$ cm, 0 cm, and -4.5 cm, where the midplane corresponds to $z = 0$ cm. As shown in this figure, both $I_s$ and $V_f$ have peak values around $R = 10$ cm radially and $z = 0$ cm vertically. This radial position of the peak value is close to the position of the upper hybrid resonance (UHR) layer rather than that of the ECR layer. Therefore, we suspect that the plasma is initiated by the ECR as described above and further heated by the UHR.

**Figure 2.** 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).

**Figure 3.** Radial profiles of (a) ion saturation currents and (b) floating potentials measured using Langmuir probes at $z = +4.5$, 0, -4.5 cm. The midplane corresponds to $z = 0$ cm.

**Figure 4.** Radial profiles of the ion saturation currents at $z = (a) +4.5$ cm, (b) 0 cm, and (c) -4.5 cm in the ECH pre-ionized plasma. The current in the vertical field coil was scanned from 0 A to -30 A. Vertical field was in the downward direction.
It was found that the profile of $I_\alpha$ is varied by the vertical magnetic field. Figure 4 shows the radial profiles of the $I_\alpha$ at $z = (a) +4.5 \text{ cm}$, (b) 0 cm, and (c) -4.5 cm. The toroidal magnetic field is in the clockwise direction in the top view. The current in the vertical field coil $I_{VF}$ was scanned from 0 A to -30 A. The negative sign of $I_{VF}$ corresponds to the downward direction of the vertical field. As shown in this figure, $I_\alpha$ at $z = +4.5 \text{ cm}$ decreases while $I_\alpha$ at $z = -4.5 \text{ cm}$ increases with increasing $I_{VF}$. This suggests that the plasma shifts downward in the case with the larger vertical field. The mechanism of this shift will be discussed later.

Another important physics is the fluctuation of plasma parameters which are considered to be correlated with the plasma confinement. Figure 5 shows that large fluctuation exists in the $I_\alpha$ of the ECH pre-ionized plasma. No vertical field was applied in figures (a-c). Same analyses were conducted in the case that the vertical field was applied, which are shown in figures (d-f).
ECH plasma. The frequency spectrum of the fluctuation is shown in figure 5(b). Fluctuation having frequencies of less than 100 kHz is dominant. Figure 5(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 = 13 cm, although the peak location of the profile of I_s itself is around R = 10 cm. No vertical field was applied in figures 5(a-c), however, we have found that the fluctuation can be suppressed by imposing the vertical magnetic field. Same analyses as shown in figures 5(a-c) were conducted in the case that the vertical field was applied, which are shown in figures 5(d-f). One can see that the fluctuation is almost completely suppressed. Note that several peaks having frequencies of larger than 100 kHz in the frequency spectrum in figure 5(e) are identical to those in the noise.

Fluctuations in the ECH plasmas were suppressed by applying not only the vertical field but also the helical field. Figure 6 shows the dependence of the fluctuation level of I_s on the vertical field or the helical field. Fluctuation of I_s decreases with the variation of I_VF from 0 to 5 A and 0 to -5 A, and I_HF from 0 to 10 A. Suppressed fluctuation level is kept for larger I_VF and I_HF.

4. Discussion

In the previous section, we have stated that the profile of I_s in the pre-ionized ECH plasma shifts downward vertically by applying the vertical magnetic field in the downward direction. In this experiment, toroidal field is in the clockwise direction; therefore, this shift of I_s profile has same direction to that of the ∇B-drift of the ions. However, ∇B-drift of the ions might not be appropriate for the mechanism of the shift of I_s profile because I_s is proportional to the electron density. We suspect that another candidate of this shift is concerned with the E×B toroidal flow generated by the radial electric field as shown in figure 3(b) and the vertical magnetic field. In the case that the vertical field is applied to the simple toroidal magnetic field, the shape of magnetic field line becomes helically spiral. If there are toroidal flows in plasmas, the particles will move along the spiral magnetic field line and they will have the vertical component of the velocity. Indeed, we also have experimental results with the counter-clockwise toroidal field which are consistent with this model.

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.

The ECH plasma which is investigated in this study is the pre-ionization phase of a tokamak operation. Therefore, we are trying to induce plasma currents using Ohmic heating. 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. On the other hand, the calculation of tracing magnetic line has revealed that TOKASTAR-2 device has a characteristic to form the magnetic surface by applying outer helical field, even though the plasma current is not induced [14]. 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.

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. 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 profile shifts vertically in cases that the vertical magnetic field is applied. 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.

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[1] Ikuta K 1968 J. Phys. Soc. Jpn. 25 1484
[2] Furth H P and Hartman C W 1968 Phys. Fluids 11 408
[3] Ohkawa T 1981 Proc. 3rd Stellarator Workshop (Moscow, 1981) 1 111
[4] Sheffield G V, Christensen U R and Furth H P 1981 Bull. Am. Phys. Soc. 26 860
[5] Todd T N 1990 Plasma Phys. Control. Fusion 32 459
[6] Moroz P E 1996 Phys. Rev. Lett. 77 651
[7] Pedersen T S and Boozer A H 2002 Phys. Rev. Lett. 88 205002
[8] Yamazaki K and Abe Y 1985 Research Report of the Institute of Plasma Physics, Nagoya, Japan IPPJ-718
[9] Yamazaki K and Kubota Y 2005 Proc. Plasma Science Symposium 2005 and the 22nd Symposium on Plasma Processing (PSS2005/SPP-22) (Nagoya, 2005,) P3-094
[10] Taira Y, Yamazaki K, Arimoto H, Oishi T and Shoji T 2010 Plasma and Fusion Res. 5 S1025
[11] Yamazaki K, Taira Y, Oishi T, Arimoto H and Shoji T 2009 J. Plasma Fusion Res. SERIES 8 1044
[12] WVII- A Team 1980 Nucl. Fusion 20 1093
[13] Fujita J, Itoh S, Kadota K, Kaneko O, Kawahata K, Kawasumi Y, Kuroda T, Matsuoka K, Matsuura K, Miyamoto K, Noda N, Ohkubo K, Oka Y, Sakurai K, Sato K, Sato M and Tanahashi S 1981 IEEE Transaction on Plasma Science PS-9 180
[14] Oishi T, Yamazaki K, Okano K, Arimoto H, Baba K, Hasegawa M and Shoji T 2010 J. Plasma Fusion Res. SERIES 9 69