Measurement of Plasma Behavior with High Speed Cameras in TOKASTAR-2*)

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The position and shape of plasma were evaluated in TOKASTAR-2 by high-speed cameras. In tokamak experiment, improvement of the plasma equilibrium control by adjusting the vertical field was observed in the tangential sightline. The plasma center was located at the equatorial plane ($Z = 0$ cm) and the plasma disappeared in contact with the inner legs of TF coils. In helical experiment, it was observed in the radial sightline that the plasma was stable below the equatorial plane when the EC resonance layer was located within the last closed magnetic surface.

Keywords: TOKASTAR, tokamak, stellarator, hybrid confinement, tokamak discharge, helical field applied, high-speed camera

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1. Introduction

For compact and low-cost coil designs and a low aspect ratio system without disruption, tokamak-stellarator hybrid confinement system called TOKASTAR was proposed [1]. To study the TOKASTAR configuration, TOKASTAR-2 device was designed and constructed. This device is able to generate tokamak and helical configurations independently by using different types of coils. The main purpose of TOKASTAR-2 experiment is to evaluate the effect of helical field application on tokamak plasma and the effect of the plasma current on compact stellarator configurations.

Figure 1 shows the coil system of TOKASTAR-2 device. It consists of six kinds of coils; eight Toroidal Field (TF) coils, three-block Ohmic Heating (OH) coils, a pair of Pulsed Vertical Field (PVF) coils, a pair of static Vertical Field (VF) coils, two outboard Helical Field (HF) coils, and four Additional Helical Field (AHF) coils. The inner legs of TF coils are covered by stainless steel plates as the limiters. VF coils are installed outside the vacuum vessel and the other coils are in it. Capacitors are used in circuits for TF coils, OH coils and PVF coils, while DC power sources are used for VF coils, HF coils and AHF coils. The magnetic field strength in the plasma center is $B_t \sim 0.1$ T. The electron cyclotron resonance (ECR) heating (2.45 GHz) is used for the pre-ionization and the injection power is ~1.4 kW. Nitrogen gas is used as working gas.

The TF coils, the OH coils and the PVF coils are used for tokamak plasma experiment. To improve tokamak

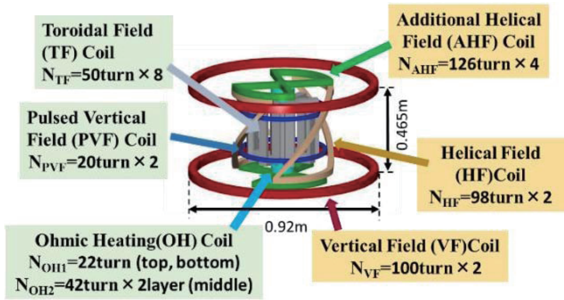

Fig. 1 Coil system of TOKASTAR-2 device.

equilibrium control, the optimal parameters of the capacitors for the PVF coil circuit were determined by evaluating the influence of the large eddy current induced in the vacuum vessel in the numerical simulation [2]. In the helical plasma experiment, the magnetic field generated by the VF coils, the HF coils and the AHF coils are added to the ECH plasma with the toroidal field only [3, 4]. In this paper, the results of improvement of the tokamak plasma equilibrium control by the vertical magnetic field adjustment and the helical field application to the ECH plasma are shown. The plasma position and shape are evaluated by the light intensity distribution of the high-speed camera images.

2. Experimental Setup and Condition

The left side drawing of Fig. 2 shows the top view of TOKASTAR-2 device and camera sightlines. Two high-speed cameras (FASTCAM ULTIMA-SE and FASTCAM SA4, PHOTRON Inc.) were used in TOKASTAR-2. In this paper, we use images taken by one of the cameras (FASTCAM SA4, PHOTRON Inc.); a frame of 320 × 160

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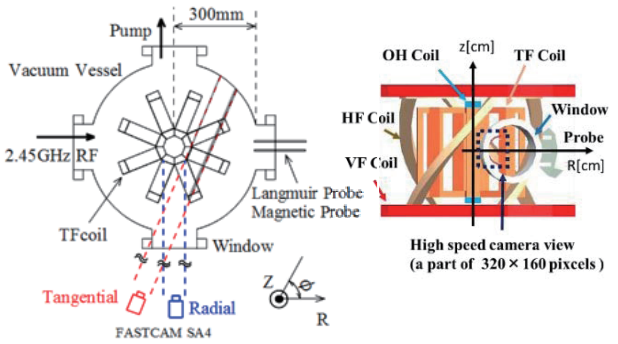

Fig. 2 (Left) Top view of high speed camera sightlines. (Right) Side view in the tangential direction.

pixels at 60000 frames per second (FPS) was used in the tangential direction and a frame of 320 × 240 pixels at 40000 FPS was used in the radial direction. The aperture diaphragm value was F8 in the tangential direction and F1.4 in the radial direction. The point of focus was in the cross-section of $\varphi = 0°$ in the tangential direction. Because the plasma was in the shape of a circular torus, light emission from the plasma in front of and behind the focus cross-section was also taken on the images by the line integral effect. The horizontal angle of view was 7.3° and the vertical angle of view was 3.7° in the tangential direction. The field of view is limited by the window flange for the high-field side and by the outer legs of a TF coil ($\varphi = -67.5°$) for the low-field side. The right side drawing of Fig. 2 shows the side view of the field of view in the tangential direction. The camera image acquisition was initiated by an external timing trigger synchronized with plasma operation sequence. The image data are transferred to a PC for storage and analysis.

3. Tokamak Plasma Experiment

After determining the optimal parameters of the capacitors for the PVF coil circuit, we adjusted the charging voltage of the capacitor (V_{PVF}). Figure 3 shows time evolution of the PVF and OH coil currents (I_{PVF}, I_{OH}), the plasma current and the loop voltages measured for three values of V_{PVF} (0.38 kV, 0.42 kV and 0.50 kV). In this experiment, the charging voltage of the capacitor of the OH coils circuit was ~2 kV for all cases. In TOKASTAR-2, one-turn loops are installed at the four inner corners of the TF coils (R = 0.06 m, Z = ±0.13 m and R = 0.18 m, Z = ±0.10 m) to measure applied loop voltage in the toroidal direction. The voltage of inside one-turn loops is mainly affected by the magnetic flux change due to the OH coil current and the voltage of the outside loops is affected by the magnetic flux change due to OH coil and PVF coil current. Therefore, the outer loop voltage is larger at the plasma breakdown and then decreases faster than the inner one.

Figure 4 shows a part of the images taken tangentially at 60000 FPS with 320 × 160 pixels per frame. In Fig. 4 (a), images are shown at an interval of 3 frames (50 µs) from the plasma breakdown (2.5833 ms), except for the 4th flame. In Figs. 4 (b) and (c), images are shown at an interval of 5 frames (about 83.3 µs). In Fig. 5, the peak values and durations of the plasma current are plotted as a function of V_{PVF}.

When V_{PVF} was low (blue curves in top of Fig. 3), dou-

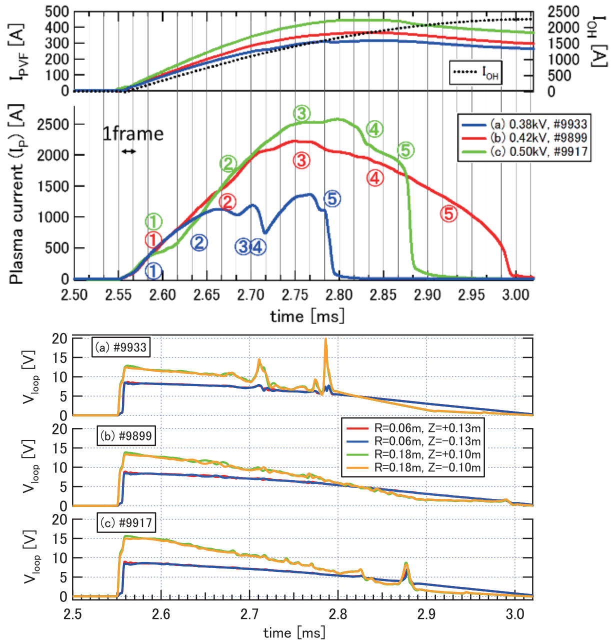

Fig. 3 Comparison of measured (Top) PVF coil current and plasma current waveform and (Bottom) loop voltages at R = 0.06 m, Z = ±0.13 m and R = 0.18 m, Z = ±0.10 m.

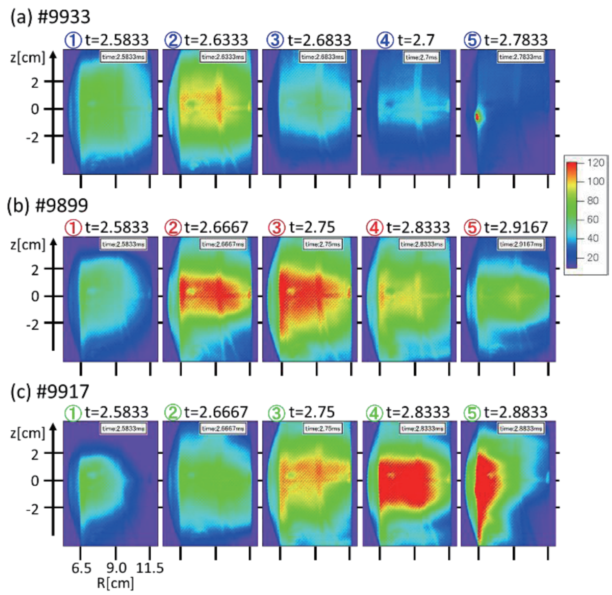

Fig. 4 Time evolution of images in tokamak discharge experiments for, (a) V_{PVF} = 0.38 kV, (b) V_{PVF} = 0.42 kV, and (c) V_{PVF} = 0.50 kV.

ble or more peaks were seen in the plasma current waveform. As shown in Fig. 3, the large spikes were observed in the outer loop voltages (R = 0.18 m, Z = ±0.10 m), accompanied by rapid decrease in the plasma current. These spikes were caused by the instantaneous flux changes at the one-turn loops, which indicates that the plasma position and/or the plasma shape were changed suddenly. In addition, the light intensity from the plasma in the image at 2.6833 ms (3rd frame) was weaker than that in the image at 2.6333 ms (2nd frame). The light intensity from the plasma in the image at 2.7 ms (4th frame) was also weaker than that in the image at 2.6833 ms (3rd frame) as shown in Fig. 4 (a). Radial size of TF coils is 60 mm ≦ R ≦ 180 mm, but imaging section can be taken only for 65 mm ≦ R ≦ 115 mm. If the plasma moves outside the field of view, the low light intensity of images would be observed by the influence of the line integral effect. Accordingly it is considered that when the plasma current increases, the plasma moved in the outward radial direction because of insufficient vertical field and crushed in contact with the outer legs of TF coils.

On the other hand when V_{PVF} was high (green curves in top of Fig. 3), plasma current reached 2.6 kA, but the discharge duration was short and the plasma current decreased sharply as shown in Fig. 3 and Fig. 5. In addition, it was seen that the plasma current rise rate dropped in a short period during the current ramp. When the plasma current decreased sharply and the plasma current rise rate dropped, the plasma was crushed in contact with the inner legs of TF coils in the image (2.8833 ms, 5th frame), which indicates that vertical field was in excess.

By adjusting V_{PVF}, the discharge duration was extended and the plasma current reached 2.2 kA as shown in top of Fig. 3 (red curves) and Fig. 5. Spikes in the one-turn loop voltages were not seen and the loop voltages gradually decreased with decreasing OH and PVF coil current. As shown in Fig. 4, the plasma was located stably in contact with the inner legs of the TF coil and the plasma center was located on the equatorial plane (Z = 0 cm). In addition, the plasma disappeared with a gradual decreasing plasma current in contact with the inner wall. The above results indicate that tokamak plasma equilibrium control is improved by adjusting the vertical field.

4. Helical Field Application on ECH Plasma Experiment

Helical plasma confinement experiments is carried out using the TF coils, the VF coils, the HF coils and the AHF coils. The purpose is to produce closed magnetic surfaces using these coils and confine the plasma within them. The currents in the VF coils, the HF coils and the AHF coils were determined to make closed magnetic surfaces using a magnetic field tracing code HSD [4, 5]. Figure 6 shows that the position of ECR layer and the last closed magnetic surfaces in the case of I_{VF} = 0.10 kAT, I_{HF} = 2.55 kAT, I_{AHF} = 2.875 kAT (DC power sources) for three different TF coil currents. In TOKASTAR-2, capacitors were used in the circuit for the TF coils, so the position ECR layer and also the last closed magnetic surface were changed by change in the TF coil current. To obtain high temperature plasma, it is necessary to locate the ECR layer within the closed magnetic surface. This condition is achieved when the TF coil current is larger than 120 A.

Figure 7 shows the images taken in the radial direction at 40000 FPS with 320 × 240 pixels per frame in the case of ECH plasma and helical plasma. The images are shown at an interval of 20 frame (0.5 ms). The light intensity of the right half of images is larger because of the reflection

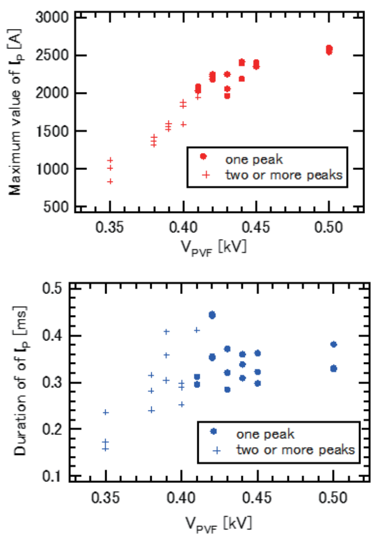

Fig. 5 (Top) The peak value of plasma current and (Bottom) the duration of plasma current as function of the charging voltage of the capacitor for the PVF coil circuit.

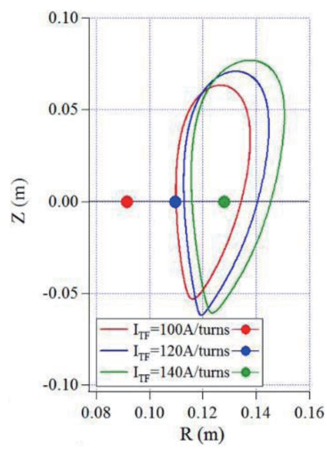

Fig. 6 The position of EC resonance layer (symbols) and the last closed magnetic surfaces calculated with HSD, for three values of the TF coil current. Red, blue and green symbols and curves denote the case with the TF coil current of 100 A, 120 A and 140 A, respectively.

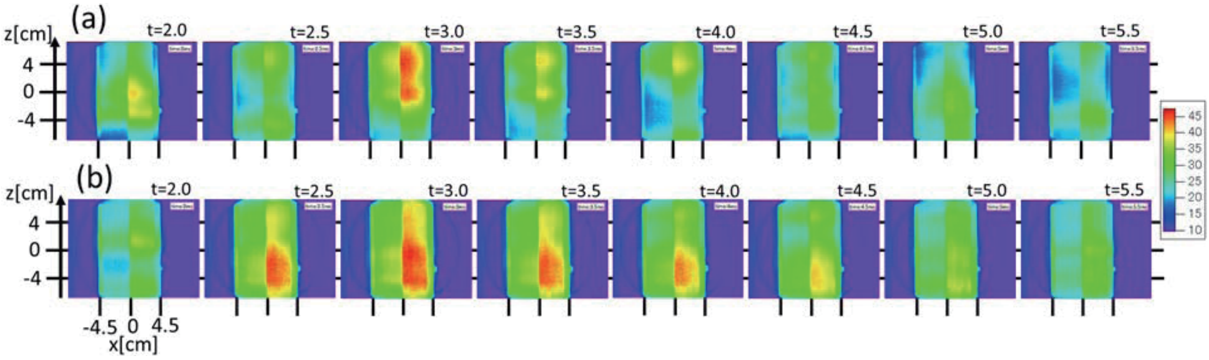

Fig. 7 Color images taken in the radial direction for (a) ECH plasma (TF+RF), (b) helical plasma (TF+RF+VF+HF+AHF).

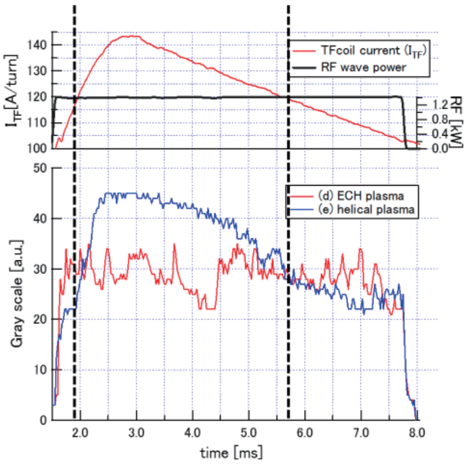

Fig. 8 (Top) Waveform of the TF coil current (in red) and the EC power (in black). (Bottom) Signals of light intensity of pixel at $Z = -4$ cm without (in red) and with (in blue) helical field application.

by the stainless steel plate on the inner leg of the right hand side TF coil. Note that no stainless steel plate was installed on the left hand side TF coil. As shown Fig. 7 (a), the ECH plasma was oscillating in the vertical direction. On the other hand, the helical plasma showed no oscillation and was stable below the equatorial plane. The plasma image seem to be shifted to the lower position compared to the last closed magnetic surface shown in Fig. 6. The reason of this difference is not well understood yet. One possible reason is error fields due to misalignment of field coils.

Figure 8 shows time evolution of light intensity of a pixel at $Z = -4$ cm in these images. The I_{TF} was larger than 120 A and the ECR layer was located within the closed magnetic surface between the two vertical dotted lines in Fig. 8. As shown in Fig. 8, the light intensity of helical plasma was large between the two vertical dotted lines, which indicates that generation of closed flux surfaces by helical field application contributes to the stable plasma confinement below the equatorial plane.

5. Summary

The plasma position and shape were evaluated in TOKASTAR-2 by light intensity distribution using high-speed cameras. Tokamak plasma equilibrium control was improved by adjusting the vertical field, so the discharge duration was extended and the plasma current reached 2.2 kA. The images taken tangentially showed that the plasma center was located at the equatorial plane (Z = 0 cm) and the plasma disappeared in contact with the inner legs of TF coils. Helical plasma showed no oscillations in the vertical direction and was stable below the equatorial plane when the ECR layer was located within the last closed magnetic surface.

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