J. Plasma Fusion Res. SERIES, Vol. 8 (2009)

Observation of Radial Displacement of Translated Field Reversed Configuration Plasma Using Computer Tomography at Two Different Cross Sections

Satoru YOSHIMURA and Shigefumi OKADA

Center for Atomic and Molecular Technologies, Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan

(Received: 27 August 2008 / Accepted: 1 December 2008)

Radial displacement of field reversed configuration (FRC) plasma was observed in translation experiments using computer tomography (CT) at two different cross sections in the FIX machine. Two sets of CT devices were installed at the upstream and downstream sides of the confinement chamber. Each CT device has three arrays of detectors sensitive to the near-infrared radiation. The Fourier-Bessel inversion technique was employed to reconstruct the two-dimensional distributions of light emitted from the FRC plasma. In some cases, the peak of the reconstructed emission profile at both upstream and downstream sides was displaced from the center in the same direction, suggesting that the FRC plasma was displaced as a rigid body in the radial direction without tilting.

Keywords: radial displacement, translation, field reversed configuration, computer tomography.

1. Introduction

The field reversed configuration (FRC) is a promising candidate for the D^3He fusion reactor because of its high β value [1]. Mostly, FRC plasmas are produced in theta pinch devices which are made of a quartz discharge tube and massive high voltage pinch coils.

On the FIX machine [2], the FRC plasma produced in a quartz tube is translated to a metal confinement chamber for the improvement of the accessibility to additional heating facilities (e.g., neutral beam injection [3]) [4]. Internal magnetic probe measurements showed that translated FRC plasmas were displaced from the center of the cross section of the metal chamber [5,6]. Similar phenomena have been observed in other FRC machines [7,8]. Although the internal magnetic probe seems to be a powerful diagnostic tool for the investigation of the internal structure of the FRC plasma, the lifetime of the plasma is significantly shortened by the insertion of the magnetic probes. The profile measurement of radiation from plasmas seems to be effective because it does not disturb the plasmas. In an earlier work, we have established a computer tomography (CT) device for the investigation of translated FRC plasmas [9,10]. In some cases, the center of the reconstructed light emissivity profile was observed to be displaced from the chamber center [9]. This observation suggests that the plasma was tilting in the axial direction or that the plasma was displaced in the radial direction as the rigid body without tilting. However, we could not distinguish the tilting and the rigid displacement without tilting. The arrangement of multiple CT devices in the axial direction enables us to distinguish the tilting from the rigid displacement. As a start of such measurement we have installed two sets of CT devices on the FIX machine [11]. In a previous paper [12], we have reported the observation of tilting activities of the FRC plasma with the CT system. In this paper, observations of the radial displacement of the FRC plasma without tilting and its temporal evolution are presented.

2. Experimental Apparatus

The FIX machine has the formation region and the confinement region [2]. The formation region consists of a quartz tube (2.0 m in length and 0.27 m in diameter) and theta pinch coils. In this region, the FRC plasma is produced from the deuterium gas by the theta pinch discharge. Then, the plasma is moved to the confinement region. The confinement region is composed of the central straight section and the mirror field sections at both downstream side and upstream side ends, as shown in Fig. 1(a). The central section is composed of quasi-static magnetic field coils and a metal vacuum chamber. The strength of quasi-static magnetic field is about 0.04 T. Figure 1(b) shows the cross-sectional view of the central section. The inner diameter of the metal chamber is 80 cm. The metal chambers of the mirror field

author's e-mail: yosimura@ppl.eng.osaka-u.ac.jp

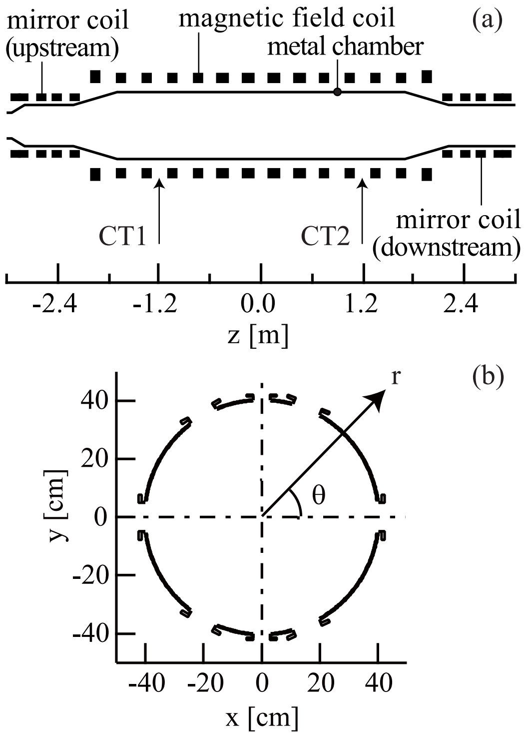

Fig.1 (a) Schematic drawing of the confinement region of the FIX machine. Two computer tomography devices (CT1 and CT2) are located at the axial sections of z = -1.2 and 1.2 m. (b) Cross-sectional view of the metal chamber of the central section.

sections are tapered. The strength of magnetic mirror field is about 0.12 T. The typical line averaged electron density and the pressure balance temperature of the translated FRC plasma are 5 x 10^{19} m^{-3} and 150 eV, respectively.

In the confinement region, 35 magnetic probes whose axes are oriented in the axial (z) direction are installed just inside the metal chamber wall and are located every 10-15 cm in the z direction. The time evolution of the axial separatrix radius profile of the FRC plasma can be obtained by the excluded flux measurement using these magnetic probes [13,14]. Electrons and ions in FRC plasmas are lost along the open magnetic field lines outside the separatrix and steep density gradient appears near the separatrix. Therefore, the measured axial separatrix radius profile corresponds to the shape of the core plasma of FRC.

The CT system consists of two identical CT devices [11]. Two CT devices are located at z = -1.2 and 1.2 m in the confinement region [Fig. 1(a)]. The sensitive spectral range of the CT device is 720-1100 nm. Two-dimensional distributions of the light emissivity in the x-y plane perpendicular to the z axis can be reconstructed by the Fourier-Bessel inversion technique [15]. The highest reconstructable Fourier mode number is limited by the number of the detector arrays installed to surround a cross section. In the present case, we install three arrays at both

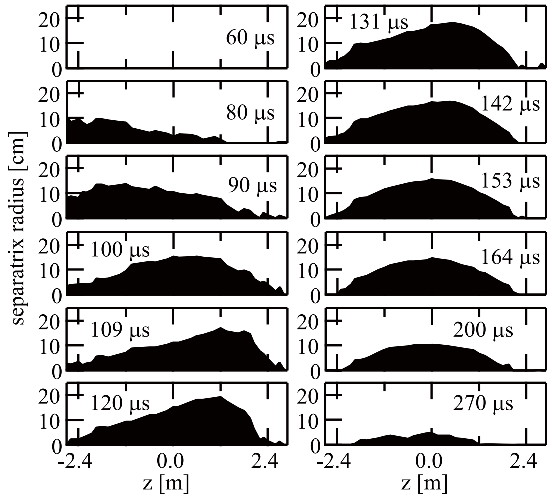

Fig.2 Temporal evolution of the axial profile of separatrix radius of a translated FRC plasma.

z = -1.2 and 1.2 m (Fig. 2 of Ref. [11]) in order to reconstruct up to n = 2 because the n = 2 rotational instability is sometimes observed in FRC plasmas [1]. It was found that the temporal evolution of the half of the full width at half-maximum of the reconstructed emission profile had the similar tendency to that of the separatrix radius during the translation [16]. This result indicates that the emission profile represents the radiation not from the low temperature plasma outside the separatrix but from the core plasma.

3. Experimental Results and Discussion

Firstly, the behavior of the FRC plasma during the translation is investigated by measuring the separatrix radius. The time evolution of the axial separatrix radius profile in the confinement region is shown in Fig. 2. Figure 2 shows that the FRC plasma produced in the formation region is translated to the confinement region at about 80 μs and the plasma is moving along z axis (90-100 μs). The peak of the axial separatrix radius profile reaches the mirror field region of the downstream side at 109 μs. The FRC plasma is reflected by the mirror field and is moving in the $-z$ direction (120 μs). The plasma settles down in the confinement region (131-142 μs) and the translation is complete at 153 μs. Then, the separatrix radius decreases gradually (164-270 μs) and the FRC plasma disappears at about 300 μs.

The plasma behavior in the x-y plane is investigated by reconstructing the light emissivity profiles from the photodiode signals. Figure 3 shows the temporal evolution of the reconstructed profiles of the light emissivity at z = -1.2 m. The intensity of the light emissivity is very small at 109 μs, as shown in Fig. 3(a). Then, the emission begins to increase [Figs. 3(b)-3(c)]. The emission signal reaches the maximum at 142 μs [Fig. 3(d)]. Then, the intensity of emission decreases gradually,

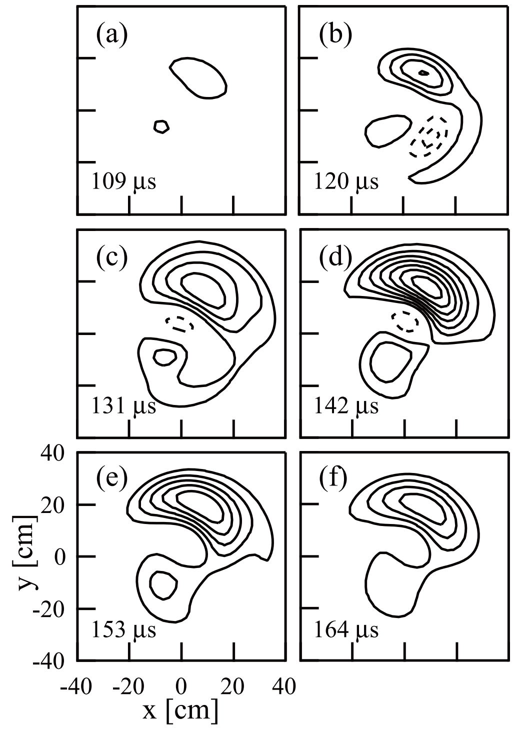

Fig.3 Reconstructed light emissivity profiles of the translated FRC plasma at the axial section of z = -1.2 m in linear-scale intensity. Dashed contours correspond to negative components.

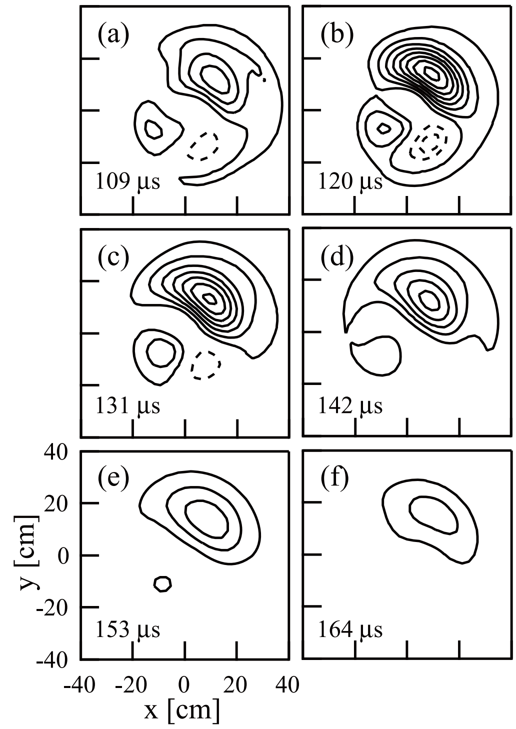

Fig.4 Reconstructed light emissivity profiles of the translated FRC plasma at the axial section of z = 1.2 m in linear-scale intensity. Dashed contours correspond to negative components.

as shown in Figs. 3(e)-3(f). In Figs. 3(b)-3(f), the peak of the reconstructed profile is displaced from the center of the chamber. The distance between the peak and the center is about 20 cm. In addition, a crescent-shaped structure and negative components can be seen.

Figure 4 shows the temporal evolution of the reconstructed profiles at z = 1.2 m. The shape of the profile is similar to those in Fig. 3. The emission signal begins to increase at 109 µs [Fig. 4(a)] and reaches the maximum at 120 µs [Fig. 4(b)]. Then, the intensity of emission decreases gradually [Figs. 4(c)-4(f)]. This difference between the temporal evolution of the reconstructed profile at z = -1.2 m and that at 1.2 m is due to the movement of the FRC plasma along the z axis.

Then, the light emissivity profile at z = -1.2 m and that at 1.2 m are reconstructed every 5 µs from the phtodiode detector signals. The peak intensities, I_{peak}, of the reconstructed profiles at z = -1.2 and 1.2 m are plotted by open circles and closed triangles in Fig. 5(b). In this shot, the intensity of the photodiode signal begins to increase after 100 µs. Therefore, I_{peak} is plotted after 100 µs. I_{peak} at z = -1.2 m and that at z = 1.2 m reach maximum at 140 and 120 µs, respectively. For comparison, the time evolution of the separatrix radius is shown in Fig. 5(a). Figure 5(a) shows that the separatrix radii at z = -1.2 and 1.2 m also reach peak value at about 140 and 120 µs, respectively. In Figs. 5(c) and 5(d), the locations of the peak of the reconstructed profiles are plotted in the polar coordinate (r, θ) [Fig. 1(b)]. Figures 5(c) and 5(d) correspond to the amount and the direction of the radial displacement, respectively. Figures 5(c) and 5(d) show that the location of the peak of the reconstructed profile at z = -1.2 m is similar to that at z = 1.2 m, suggesting that the FRC plasma is displaced as a rigid body in the radial direction in this shot.

In Figs. 3 and 4, the crescent-shaped structure and the negative components appear. In our earlier paper [12], a computer simulation of Gaussian-type test profile reconstruction showed that three detector arrays were enough to reconstruct the light emissivity profile in the case of small radial displacement. On the other hand, the crescent-shaped structure and some artifacts appeared in the reconstructed contour maps when the radial displacement was relatively large, as shown in Ref. [12]. The reconstructed profiles in Figs. 3 and 4 are similar to those in Ref. [12] (Fig. 6 of Ref. [12]). Figure 6 shows the peak intensity of reconstructed profile as a function of radial displacement of Gaussian-type test profile. The dashed line in Fig. 6 corresponds to the peak intensity of the Gaussian-type test profile. It is found that the peak intensity of reconstructed profile is different from that of the test profile when the radial displacement of the test profile is larger than 15 cm. It seems that more than three detector arrays are required for the accurate reconstruction when the radial displacement is larger than 15 cm.

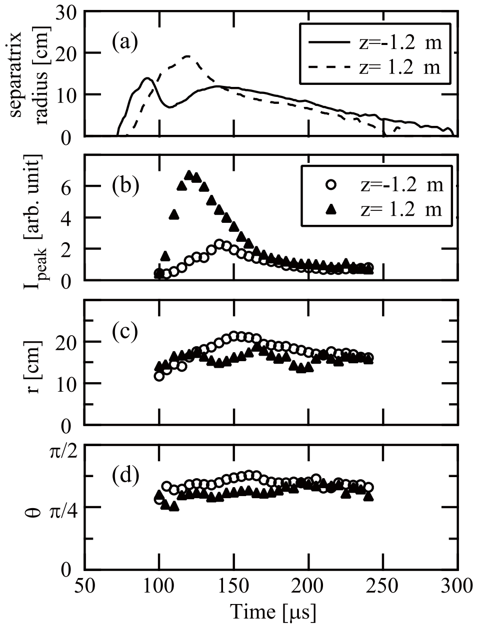

Fig.5 (a) Time evolution of separatrix radius at the axial sections of two tomography devices. (b) Temporal evolution of the peak intensity of the reconstructed light emissivity profiles. (c)-(d) Time evolution of the location of the peak of the reconstructed light emissivity profiles in the polar coordinate.

We analyzed 49 shots of FRC plasmas with the CT system. Radial displacements were observed in 27 shots. In 13 shots among 27 shots, the FRC plasma was found to be tilted in the axial direction. The direction and amount of the radial displacement were different shot by shot. The FRC life times of displacement shots were not different from those of the ordinary shots. The cause of the radial displacement has not been confirmed yet. Further investigations of the dependence of the radial displacement on plasma parameters are required. We think that detailed measurement of the plasma behavior in the formation region before the translation is required for the confirmation of the cause of the radial displacement.

4. Conclusion

In the FIX machine, the FRC plasma produced in the quartz tube is translated to the metal confinement chamber. Two sets of CT devices are installed at the upstream and downstream sides of the confinement chamber for the investigation of the translation of FRC plasmas. Each CT device has three detector arrays. Two-dimensional distributions of the light emissivity of the translated FRC plasma are reconstructed using the Fourier-Bessel inversion technique. In some cases, the peak of the reconstructed emission profile at both sides was displaced from the center, suggesting that the FRC plasma was displaced as the rigid body in the radial direction. We think that this type of CT system will be useful for the investigation in FRC experiments.

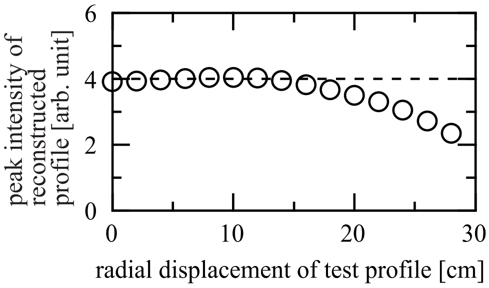

Fig.6 The peak intensity of reconstructed profile as a function of radial displacement of Gaussian-type test profile. The dashed line corresponds to the peak intensity of the test profile.

Acknowledgments

The authors would like to express their gratitude to other members of the FIX group for help in the experiments. This work was partially supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

[1] M. Tuszewski, Nucl. Fusion **28**, 2033 (1988).
[2] S. Okada, M. Inomoto, S. Yamamoto, T. Masumoto, S. Yoshimura, K. Kitano, Nucl. Fusion **47**, 677 (2007).
[3] T. Asai, Y. Suzuki, T. Yoneda, F. Kodera, M. Okubo, S. Okada, S. Goto, Phys. Plasmas **7**, 2294 (2000).
[4] H. Himura, S. Okada, S. Sugimoto, S. Goto, Phys. Plasmas **2**, 191 (1995).
[5] A. Shiokawa, S. Goto, Technol. Repts. Osaka Univ. **41**, 235 (1991).
[6] H. Himura, H. Wada, S. Okada, S. Sugimoto, S. Goto, Phys. Rev. Lett. **78**, 1916 (1997).
[7] M. Tuszewski, D. C. Barnes, R. E. Chrien, J. W. Cobb, D. J. Rej, R. E. Siemon, D. P. Taggart, B. L. Wright, Phys. Rev. Lett. **66**, 711 (1991).
[8] K. Fujimoto, A. Hoshikawa, S. Ohmura, T. Takahashi, Y. Nogi, Y. Ohkuma, Phys. Plasmas **9**, 171 (2002).
[9] S. Yoshimura, A. Nakamura, K. Shinagawa, S. Sugimoto, M. Okubo, S. Okada, S. Goto, Trans. Fusion Technol. **39**, 374 (2001).
[10] S. Yoshimura, K. Shinagawa, S. Sugimoto, K. Kitano, S. Okada, S. Goto, IEEE Trans. Plasma Sci. **30**, 60 (2002).
[11] S. Yoshimura, S. Sugimoto, S. Okada, Trans. Fusion Sci. Technol. **51**, 376 (2007).
[12] S. Yoshimura, S. Sugimoto, S. Okada, Phys. Plasmas **14**, 112514 (2007).
[13] M. Tuszewski, Phys. Fluids **24**, 2126 (1981).
[14] M. Tuszewski and W. T. Armstrong, Rev. Sci. Instrum. **54**, 1611 (1983).
[15] Y. Nagayama, J. Appl. Phys. **62**, 2702 (1987).
[16] K. Shinagawa, S. Yoshimura, S. Sugimoto, K. Kitano, A. Nakamura, S. Okada, S. Goto, J. Plasma Fusion Res. SERIES **5**, 215 (2002).