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Magnetic Structures inside the Separatrix on Field-Reversed Configuration Plasmas

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Abstract

Separatrix shapes and internal structures of a field-reversed configuration (FRC) plasma are determined by comparing the measured magnetic fluxes with the Grad-Shafranov equation. This analysis also suggests a width of an edge-layer plasma $w\rho_i$ (w is the number of ion gyro-radius ρ_i), a beta value at the separatrix β_s, and the formation of magnetic islands near the field null. In order to confirm these findings by the magnetic method, a radiation power density of the FRC is measured. It is found that the w and β_s values agree well with those obtained by the radiation measurement. However, the positions of the magnetic islands do not coincide with those appearing in an intensity contour map of the radiation. Asymmetrical profiles of the radiation are also discussed with respect to the nonconcentricity of the pressure constant surface. The measured profiles can be explained when the center of the FRC is shifted by 0.1–0.2r_s (r_s is a separatrix radius) without any shift of the separatrix surface.

Keywords:

field-reversed configuration, theta pinch, compact torus, separatrix shape, internal structure, magnetic structure, magnetic island

1. Introduction

A field-reversed configuration (FRC) is one of the simplest toroidal plasma configurations. The FRC plasma is confined within a separatrix by a poloidal magnetic field that is generated by plasma diamagnetic toroidal currents, and has no toroidal field. It is well known that FRC plasma has many advantages including its compact, simple geometry, and its having a high plasma beta and being a natural divertor. Therefore, the physics of FRC's has been studied from experimental and theoretical points of view [1-4].

The separatrix shape of a FRC plasma is determined approximately by an excluded flux method; it is derived from the combination of a magnetic flux ϕ inside the vacuum vessel and an axial field B_z outside the plasma [5]. Although an excluded flux radius $r_{\Delta\phi}$ by this method can be measured easily and is used as a standard diagnostic system in FRC experiments, it is known that $r_{\Delta\phi}$ does not coincide with the real separatrix shape, particularly in end regions. Recently, in order to measure the separatrix shape $r_s(z)$ and the internal structure, the iterative method has been proposed [6], where the separatrix shape of the FRC is determined by comparing iteratively measured magnetic fluxes with a solution of the Grad-Shafranov equation. The magnetic structure inside the separatrix can also be obtained by solving the equation using the determined separatrix shape $r_s(z)$ and the beta value at the separatrix β_s [7]. It is found from the calculation that the magnetic islands are observed near the field null at the formation phase. Moreover, although they are coalesced once by the axial contraction of the plasma to attain the equilibrium, they appear again at the quiescent phase.

In order to confirm the β_s value and the formation of the magnetic islands optically, a radiation profile of the FRC is measured. The profile is analyzed by the Abel inversion method to obtain a radial profile of the radiation power density $i(r)$. When the plasma temperature is assumed to be uniform, β_s and the thickness of the edge-layer plasma can be estimated from $i(r)$. Then, we compare the two values obtained from the optical and magnetic methods. Moreover, the optical detector array is shifted along the vacuum vessel in order to observe the profile of line-integrated radiation intensity at several axial positions. The obtained $i(r)$ contours on the r-z plane are compared to the internal structures from the magnetic method. Finally, the nonconcentricity of $i(r)$ contours on the x-y plane is discussed.

2. Experimental apparatus

FRC plasmas are produced by a negative-biased theta-pinch device called NUCTE-III, as illustrated in Fig. 1(a) [8]. The theta-pinch coil consists of 28 coil elements; a center region has a 0.17 m radius and a mirror one has a 0.15 m

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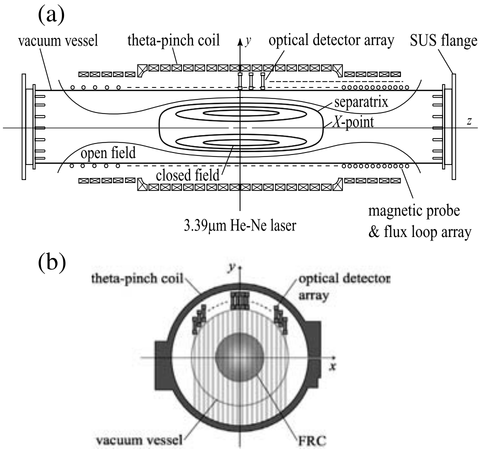

Fig. 1 (a) Experimental device NUCTE-III and (b) arrangement of the optical detector array.

radius, and both regions are connected smoothly by taper coils. Then, a mirror ratio of the field is $R_M = (0.17/0.15)^2 \simeq 1.28$ on the z-axis. The total length of the theta-pinch coil is approximately 1.5 m; the center region is 1.0 m and the mirror regions are 0.25 m. The strength of the negative bias field is –0.032 T, and that of the confinement field reaches 0.6 T on the midplane ($z = 0$) at $t = 4$ μs and decays at $t = 120$ μs in vacuum. The vacuum vessel consists of a transparent quartz tube of 0.13 m radius and 2.0 m length. FRC plasmas are produced by filling 15 mTorr deuterium into the vacuum vessel.

Magnetic probes and flux loops are installed along the vacuum vessel to measure axial field B_z and magnetic flux ϕ at multiple axial positions. These arrays are used for determining $r_{\Delta\phi}(z)$ by the excluded flux method and $r_s(z)$ by the iterative method. An array of optical detectors is shown in Fig. 1(b). A detector at $x = x_1$ can measure the radiation ranging in a wavelength 550±5 nm along an optical path parallel to the y-axis, $I(x_1) = \int i(y)\mathrm{d}y$ [9]. The line-integrated electron density is measured by a 3.39 μm helium-neon laser interferometer at $z = 0$.

Typical plasma parameters at $z = 0$ are the separatrix radius $r_s(0) \simeq 0.06$, the full length $l_s \simeq 0.8$ m, the average beta value $\langle\beta\rangle = 1 - x_s^2/2 \simeq 0.94$ (x_s: normalized separatrix radius by coil radius r_w), the average electron density $\langle n_e\rangle \simeq 3 \times 10^{21}$ m^{-3}, the sum of electron and ion temperatures $T_e + T_i \simeq 200$ eV, the configuration life time $\tau_\phi \simeq 70$ μs, and the particle confinement time $\tau_N \simeq 60$ μs during $t = 20$–30 μs. When $T_i \simeq T_e \simeq 100$ eV is assumed, a gyro-radius of deuterium ion is $\rho_i \simeq 4.1$ mm in the vacuum field $B_0 = 0.5$ T.

3. Internal structures

The separatrix shape can be determined with the edge-layer plasma in the open field region by the iterative method, and the magnetic structure inside the separatrix is calculated at the same time. For this calculation, the Grad-Shafranov equation for the magnetic flux function ψ is used as follows;

$$\frac{\partial^2\psi}{\partial r^2} - \frac{1}{r}\frac{\partial\psi}{\partial r} + \frac{\partial^2\psi}{\partial z^2} + \mu_0 r^2 \frac{\mathrm{d}p(\psi)}{\mathrm{d}\psi} = 0\,, \tag{1}$$

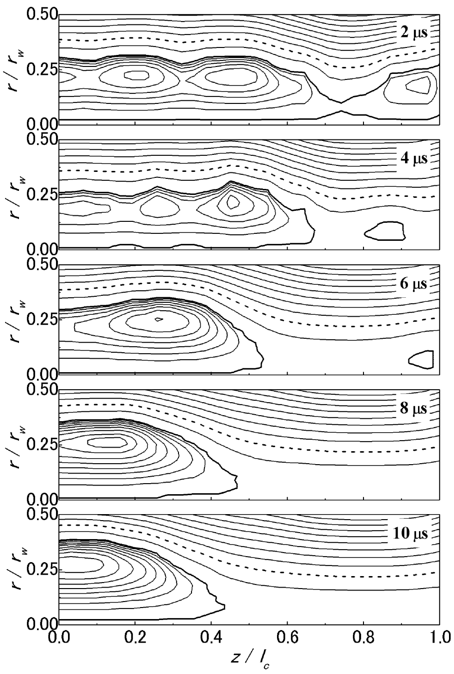

Fig. 2 Time evolution of flux contour maps at the formation phase. Dashed lines indicate the boundary of the edge-layer plasma ($\psi = \psi_{edge}$).

where μ_0 and $p(\psi)$ are, respectively, the permeability of free space and the plasma pressure. It is assumed that $p(\psi)$ has a different form corresponding to the magnetic regions $\psi < 0$ (inside the separatrix), $0 \le \psi \le \psi_{edge}$ (edge-layer region), and $\psi_{edge} < \psi$ (vacuum region), as follows;

$$p(\psi) = \begin{cases} p_s \exp\{(-\log\beta_s/\psi_n)\psi\} & \text{at} \quad \psi < 0\,, \\ p_s \exp\{-2\psi/\psi_{edge}\} & \text{at} \quad 0 \le \psi \le \psi_{edge}\,, \\ 0 & \text{at} \quad \psi_{edge} < \psi\,, \end{cases} \tag{2}$$

where p_s is the plasma pressure on the separatrix surface ($\psi = 0$), ψ_n and ψ_{edge} are flux functions at the magnetic field null ($r = R$) and at the boundary of the edge-layer [$r = r_s(0) + w\rho_i$: w is the number of ion gyro-radius ρ_i], respectively. Since the true value of ψ_n is not known in advance, the calculation is started using an appropriate value of ψ_{n0}. The solution of this calculation gives the flux at the field null ψ'_{n0}. When $\psi_{n0} \simeq \psi'_{n0}$, ψ_{n0} can be considered to be close to the true value of ψ_n. The pressure profile inside the separatrix is equivalent to the rigid rotor profile model under the assumption of uniform plasma temperature. Moreover, the profile at the edge-layer satisfies the boundary condition $p = p_s$ at $\psi = 0$, and it is assumed that $p = p_s/e^2$ at $\psi = \psi_{edge}$.

In order to investigate the behavior of the FRC plasma, the time evolution of the separatrix and the internal structure is determined by the iterative method using Eqs. (1) and (2). On the basis of this calculation at the formation phase ($t = 2$–10 μs), the flux contours are given in Fig. 2. It is seen that the closed separatrix surface starts to form at $t = 2$ μs in the region under the taper coil ($z/l_c \simeq 0.7$: normalized length by half coil length l_c) and the X-point of the main plasma moves inward by axial contraction to attain equilibrium, while the torn plasma remaining in the mirror region moves toward the coil end and fades away.

Here, we notice the magnetic structure inside the separatrix. It is seen that the closed field lines near the field null are torn into three parts at t = 2 μs. These magnetic islands coalesce into a large one by axial contraction at t = 6 μs, and after that, the large island moves toward the midplane with time to attain the equilibrium form. It is confirmed that these behaviors do not change significantly when the other pressure profiles are assumed in solving Eq. (1) [7].

4. Radiation profile of FRC

In order to estimate the amount of the edge-layer plasma and to determine the internal structures by means of an optical method, the set of optical detectors shown in Fig. 1(b) is shifted along the vacuum vessel at four axial positions (z = 0, 0.11, 0.22, and 0.33 m). The profiles $I(x)$ at t = 20 μs are depicted in Fig. 3, where (a) and (b) retain relatively symmetrical forms against x = 0, but (c) and (d) are slightly asymmetrical.

The radiation profiles can be analyzed by the Abel inversion method in order to estimate the radial profile of the radiation power density $i(r)$. Since it is confirmed that the radiation consists mainly of bremsstrahlung [9], $i(r)$ is approximately proportional to n_e^2 under the assumption of uniform temperature. Therefore, $\sqrt{i(r)} \propto n_e(r) \propto \beta(r)$. It is found that the beta value at the separatrix ($r = r_s$) is $\beta_s \simeq 0.75$ and the thickness of the edge-layer plasma is about 0.024 m at t = 20 μs on the z = 0 plane. The β_s value and the thickness of the edge-layer plasma do not change significantly during t = 10–25 μs, and remain consistent with the values analyzed by the magnetic method.

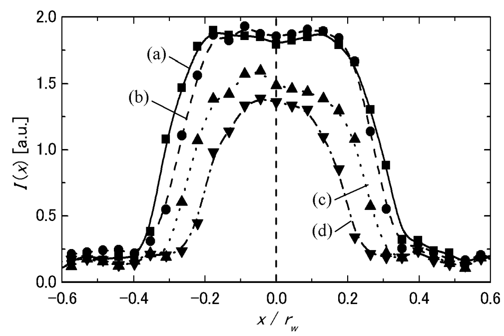

Fig. 3 Profiles of the line-integrated radiation intensity at four axial positions; (a) z = 0, (b) 0.11 m, (c) 0.22 m, and (d) 0.33 m.

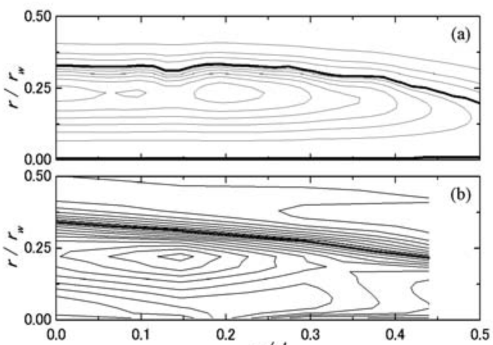

Fig. 4 Contour maps of (a) the magnetic flux and (b) the radiation power density at t = 20 μs.

An intensity contour map on the r-z plane can be formed from these $i(r)$ profiles. Figure 4(a) shows the magnetic flux contours at t = 20 μs on the discharge shown in Fig. 2, and Fig. 4(b) depicts the contours of the radiation power density $i(r)$ normalized by $i(0)$ at z = 0. Since the optical detectors are not installed beyond $z/l_c > 0.43$, the contours disappear near the end region of the FRC. It is seen that the magnetic islands in (a) and the high-density region in (b) exist at different positions, and the separatrix shape in (b) is more slender than that in (a). Next, the $I(x)$ profiles at four axial positions are compared with line-integrated square pressure along the y-axis $P(x) = \int p^2(x, y)\mathrm{d}y$, where $p(x, y)$ is the solution given in Sec. **3**. It is found that $P(x)$ comparatively agrees with $I(x)$ at z = 0 and 0.11 m, but not $I(x)$ at z = 0.22 and 0.33 m.

We discuss the asymmetry of the $I(x)$ profiles in Fig. 3(c) and (d). For this purpose, the rigid rotor profile model for the density and the magnetic field is modified including nonconcentricity as follows [10].

$$n(x, y) = n_m \mathrm{sech}^2 \left\{ K \left[\frac{(x-\delta x)^2 + y^2}{R^2} - 1 \right] \right\}, \qquad (3)$$

$$B(x, y) = B_0 \tanh \left\{ K \left[\frac{(x-\delta x)^2 + y^2}{R^2} - 1 \right] \right\}, \qquad (4)$$

where n_m is n at $r = R$, B_0 is B at the wall, and $K = \tanh^{-1}[B(r_s)/B_0]$. The value of δx which denotes the

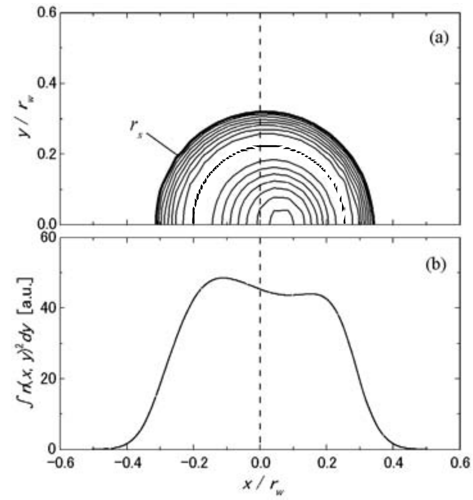

Fig. 5 (a) Contour map of the plasma density at the x-y plane and (b) the line-integrated square density profile of a nonconcentric FRC.

nonconcentricity of the $n(x, y)$ and $B(x, y)$ profiles is defined as

$$\delta x = \frac{d}{r_s}(r_s - x) , \tag{5}$$

where d is the shift distance of the central axis of the FRC from the z-axis. The $n(x, y)$ contours and an $I(x)_{r.\,r.} = \int n^2(x, y)dy$ profile in $d = 0.2r_s$ are depicted in Fig. 5(a) and (b), respectively. The profile (c) in Fig. 3 coincides well with the $I(x)_{r.\,r.}$ profile; moreover, the profile (d) can also agree with the $I(x)_{r.\,r.}$ profile when $d = 0.1r_s$. It is suggested from these analyses that the density contours inside the separatrix might be the nonconcentric profile at end regions.

5. Summary

The separatrix shapes and the internal structures of FRC plasma are determined at the same time by solving the Grad-Shafranov equation, where the pressure term not only inside the separatrix but also in the edge plasma region is assumed by an exponential function of ψ. The closed separatrix surface starts to form during $t = 2$ μs after the initiation of the confinement field in the region under the taper coil. The X-point of the FRC moves inward by axial contraction, while the torn plasma moves toward the coil end. It is noted that the closed field lines near the field null are torn into three parts at the formation phase, and they coalesce into a large island by axial contraction. The large island moves toward the midplane with time.

In order to confirm the edge plasma parameters and the formation of the magnetic islands, the radiation profile of the FRC is observed. The profile is analyzed by the Abel inversion method in order to determine the radial profile of the radiation power density. The beta value at the separatrix is 0.75 and the thickness of the edge-layer plasma is 6 times the ion gyro-radius at the quiescent phase. These findings agree with those from the magnetic analysis.

From the radiation profiles at several axial positions, the intensity contour map on the r-z plane is produced, although the profiles are asymmetrical except for that near the center region. It is found that the magnetic islands and the high-intensity region exist at different positions. An explanation of the asymmetry of the radiation profiles is attempted on the basis of the nonconcentricity of the pressure constant surface. It is found that the radiation profiles coincide with the nonconcentric profiles, the center of which is shifted from the equilibrium position by 0.1–0.2r_s without any shift of the separatrix surface.

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