# Effects of Neutral Particle Density on Equilibrium of Field-Reversed Configuration Sustained by Rotating Magnetic Field

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The effects of neutral particle density on equilibrium of field-reversed configuration (FRC) plasmas sustained by rotating magnetic fields (RMF) were investigated in the FRC Injection Experiment apparatus. Two different gas feeding methods were used to realize different neutral particle density conditions. The experimental results show that a higher current drive efficiency with full penetration of the RMF was achieved in the lower neutral particle density case. On the other hand, the plasma current in a higher neutral particle density case flowed in a narrower region near the geometric axis than in a lower neutral particle density case. The FRC equilibrium with higher neutral particle density resulted in lower current drive efficiency, possibly due to the shorter penetration length of the RMF. No significant ion spin-up was observed in the present conditions.



Keywords: field-reversed configuration, rotating magnetic field, current drive, neutral particle density

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## 1. Introduction

A field-reversed configuration (FRC) [1] is a compact toroidal plasma confined solely by a poloidal magnetic field generated by a purely diamagnetic azimuthal (toroidal) plasma current. Because an extremely high beta value is an essential property of the FRC—the FRC does not attain equilibrium for low and zero beta value—it has been believed that a huge amount of initial heating power is necessary to form the FRC equilibrium. The field-reversed theta pinch (FRTP) method [1] has been traditionally employed to produce FRC plasmas with high densities and temperatures, although the lack of a current drive or additional heating methods has limited the FRC lifetime to shorter than 1 ms.

There are some other schemes to form the FRC without large power input within a short period. A rotating magnetic field (RMF) is a major candidate to drive steady plasma current in the FRC and is also capable of generating the FRC equilibrium. Many numerical [2–7] and experimental studies [8–13] have been conducted, and long-pulse [11] or high-performance [13] plasmas have been achieved recently. Long-term FRC sustainment requires particle supply as well as power input from the RMF; therefore, a certain amount of neutral particle density (hereafter abbreviated as neutral density) is considered to be essential for steady-state sustainment. A considerably high neutral density, which leads to suppression of the ion spin-up due to electron drag [3, 7], is usually employed in numerical studies [2, 4]. On the other hand, a high neutral density is not favorable from the viewpoint of neutral beam injection (NBI) heating [14]. The neutral density outside the separatrix is expected to cause severe degradation of efficiency of NBI power deposition [15]. Thus, neutral density is an important parameter that affects the feasibility of the steady-state FRC; however, an experimental investigation focusing on neutral density has not yet been conducted.

In this study, we describe the effects of neutral density on the FRC equilibrium formed and sustained by the RMF. Two different gas feeding methods were used to obtain plasmas with different neutral densities. The experimental results show that a lower neutral density yielded higher current drive efficiency with full penetration of the RMF. A higher neutral density resulted in a narrower current profile localized near the geometrical axis, resulting in lower current drive efficiency, possibly due to the shorter penetration length of the RMF.

## 2. Experimental Setup

Figure 1 (a) shows the cross-sectional view of the FRC Injection Experiment (FIX) apparatus. Two pairs of RMF antennas are located at $r_{\mathrm{ANT}} = 33$ cm inside the metal chamber of the FIX confinement section, whose inner radius $r_{\mathrm{w}}$ is 40 cm. Due to the image current in the conducting chamber wall, the generated RMF has strong high-harmonic components [12], whose penetration property is different from the simple dipole RMF of other devices. The RMF lines of force calculated from a one-dimensional model based on full RMF penetration

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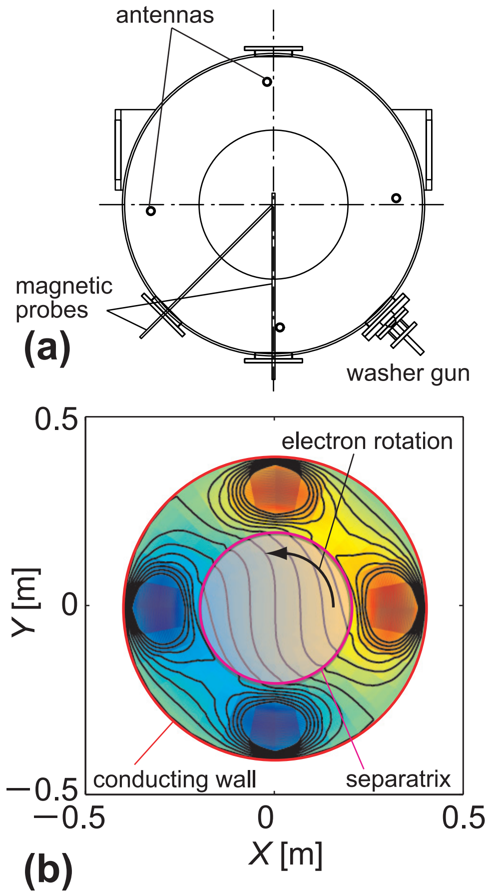


Fig. 1 (a) Cross-sectional view of the FIX device and (b) lines of force of the RMF calculated using one-dimensional model.

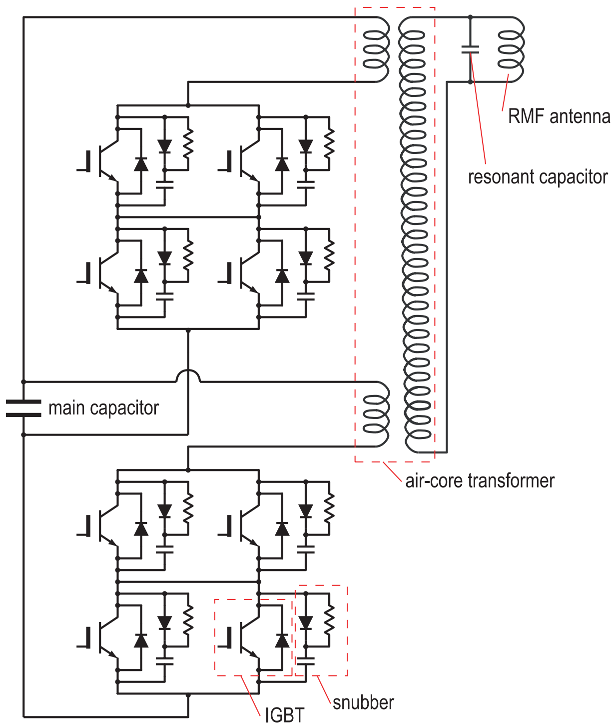


Fig. 2 Circuit diagram of the RMF power supply.

are shown in Fig. 1 (b). The fundamental component of the RMF is expected to fully penetrate into the plasma, whereas the high-harmonic components are screened at the plasma edge, because they have slower or reversed rotation frequencies compared to the fundamental component.

The two pairs of RMF antennas are energized by two independent forward-type inverter circuits, as shown in Fig. 2. Insulated gate bipolar transistors (IGBTs) with a rating voltage and current of 1200 V and 600 A, respectively, are stacked in parallel and series in order to drive a large current. The inverter circuits are gated to produce two rectangular current waveforms with a mutual phase difference of $\pi/2$ via gate driver circuits, from which the primal controller is optically insulated. An air-core transformer is used to couple the inverter circuit with the resonant circuit consisting of the RMF antennas and film capacitors. Thus, the currents flowing in the RMF antennas have nearly sinusoidal waveforms with the specified resonance frequency, which is adjustable by changing the resonant capacitance. The available range of RMF frequency is 80-160 kHz. A 2.4-mF capacitor is used as a main capacitor bank to provide quasi-dc voltage for the inverter circuits; it supplies a maximum power of 50 MW for a maximum duration of about 3 ms.

Internal magnetic probes are used to measure both radial and axial profiles of the steady-state axial magnetic field. The radial probe consists of 13 pick-up coils with radial spacings of 3 cm. The axial probe has 19 coils with axial spacings of 10 cm. The electron density is measured by a Langmuir probe.

Two different gas feeding methods are employed to achieve different conditions of neutral density. One is a simple gas filling method [16], in which the RMF sustains the plasma current and also pre-ionizes the gas. A stable FRC plasma was achieved with deuterium at a gas filling pressure of 0.03-0.06 Pa. The neutral density can be estimated from the pressure of the filled deuterium gas measured by an ionization vacuum gauge. The estimated neutral density of $n_n \sim$ 1-2$\times 10^{19}$ m$^{-3}$ was more than ten times higher than the typical electron density of the FRC plasma $n_e \sim 7 \times 10^{17}$ m$^{-3}$, resulting in a high ion–neutral collision frequency of $\nu_{in} \sim 10$ kHz.

The other gas feeding method involves the use of a washer-gun type plasma injector [17]. A highly ionized deuterium plasma is injected from the washer-gun located on the midplane of the FIX chamber. The estimated neutral density was $n_n < 5 \times 10^{17}$ m$^{-3}$, which was 20 times lower than that for gas filling, and almost equal to the electron density of $n_e \sim 5 \times 10^{17}$ m$^{-3}$. The estimated ion–neutral collision frequency was $\nu_{in} \sim 0.5$ kHz. The fact that the neutral density was lower for the washer-gun method was also confirmed by spectroscopic measurement of the plasma light emission.

## 3. Experimental Results

Figure 3 (a) and (b) show the time evolutions of the steady axial magnetic field of the FRC measured at various radial locations on the midplane for the (a) gas filling and (b) washer-gun methods. The RMF current and frequency were set to $I_{\mathrm{RMF}} = 700$ A and $\omega = 670\times10^3$ rad / s, respectively. The axial field was reversed for more than 0.5 ms for both cases as long as the RMF current was fed; however, different current drive efficiencies were achieved. The washer-gun method with lower neutral density had a larger field reversal, i.e., a larger plasma current than the gas filling method with higher neutral density. Figure 3 (c) and (d) show the evolution of the extent of field reversal $\Delta B = B_z(r_{\mathrm{w}}) - B_z(0)$ and the trapped poloidal magnetic flux $\Psi$, respectively, for both cases. The washer-gun method caused twice as large a field reversal as the gas filling method, resulting in a greatly increased poloidal flux.

Figure 4 shows the extent of field reversal as a function of bias magnetic field $B_{\mathrm{bias}}$ for both methods with different gases. The washer-gun method exhibited larger field reversal than the gas filling method in all gas species, indicating that the difference in the FRC equilibrium was caused by the effect of neutral density, and not by other

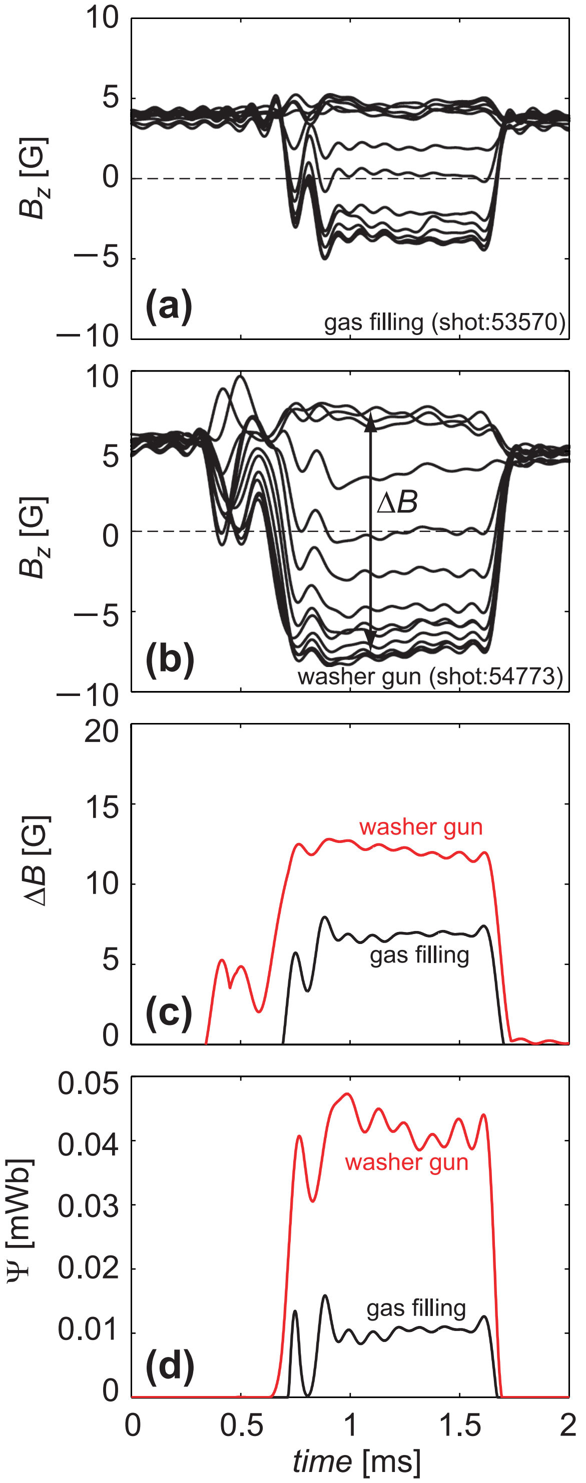


Fig. 3 Time evolutions of steady axial magnetic field of FRC measured at various radial locations for the (a) gas filling and (b) washer-gun methods. Evolutions of extent of field reversal and flux for both cases are shown in (c) and (d).

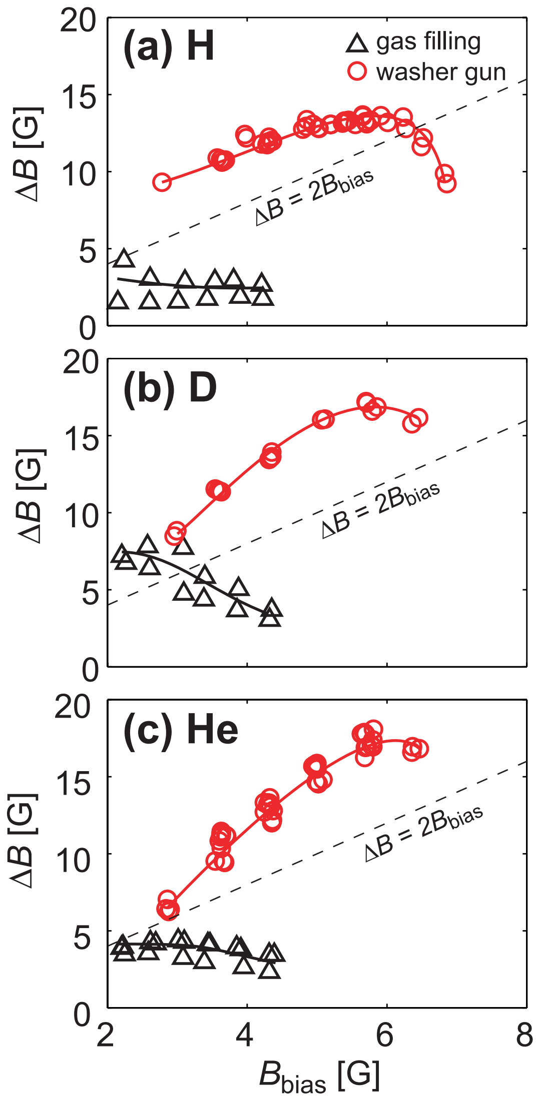


Fig. 4 Extent of field reversal of the FRC plasmas with (a) hydrogen, (b) deuterium, and (c) helium gases.

causes associated with is, such as the ionization process. In particular, the field reversal $\Delta B$ in the washer-gun method was observed to exceed $2 \times B_{\text{bias}}$, which is indicated by dashed lines in Fig. 4. Therefore, the steady magnetic pressure at the geometric axis of the plasma ($r = 0$) is even larger than that outside the separatrix. High-harmonic components of the RMF are considered to be responsible for this feature. Due to their slower or reversed rotation frequencies compared to the fundamental component, the high-harmonic components are expected to be totally excluded from the bulk plasma region, which rotates synchronously with the fundamental component of the RMF. High magnetic pressure is provided by the high-harmonic component, sustaining a higher plasma pressure around the separatrix. Thus, field reversal even larger than the external field is one of the unique features of the FRC driven by an RMF with higher harmonics [12]. On the other hand, the gas filling method showed a rather small field reversal and small plasma current driven by the RMF. Note that no closed flux surface was achieved for the gas filling method with a bias field $B_{\text{bias}}$ stronger than 5 G.

Figure 5 shows the radial profiles of (a) steady axial magnetic field $B_z$, (b) poloidal flux $\Psi$, and (c) azimuthal current density $j_\theta \equiv (1/\mu_0)\partial B_z/\partial r$ based on the assumption of axial uniformity. These quantities were measured or calculated on the midplane ($z = 0$). The triangle and circle marks correspond to the discharges with the gas filling and washer-gun methods, respectively, shown in Fig. 3 (a) and (b). The FRC with the washer-gun method was observed to have a larger separatrix radius and a larger plasma current flowing in a broader area than that with the gas filling method, as expected from the magnetic field profile shown in Fig. 5 (a). The FRC with the washer-gun method had a current density increasing almost in proportion to the radial position, indicating that the plasma current was carried mostly by synchronously rotating electrons as $j_t = e\omega_e r n_e$, where $\omega_e$ is the electron angular frequency and $n_e$ is the electron density, which was observed to have small radial nonuniformity inside the separatrix [12].

On the contrary, in case of gas filling, the FRC showed a different current density profile that was localized around the field null point. The current density showed a rather flat radial distribution, suggesting that the FRC plasma had a radially decreasing density profile. In order to compare the two cases under similar conditions, radial profiles of each quantity for the washer-gun discharge with a reduced RMF current of 400 A, which resulted in a similar separatrix radius for gas filling under the same bias field, are shown together in Fig. 5 by cross marks. The reduced RMF case showed a lower current density than the normal washer-gun method; however, both cases resulted in similar radial profiles. Thus, the difference in current density profile between the gas filling and washer-gun methods was attributed to the difference in the current drive efficiency possibly influenced by the neutral density.

The axial profile of the steady axial magnetic field $B_z$

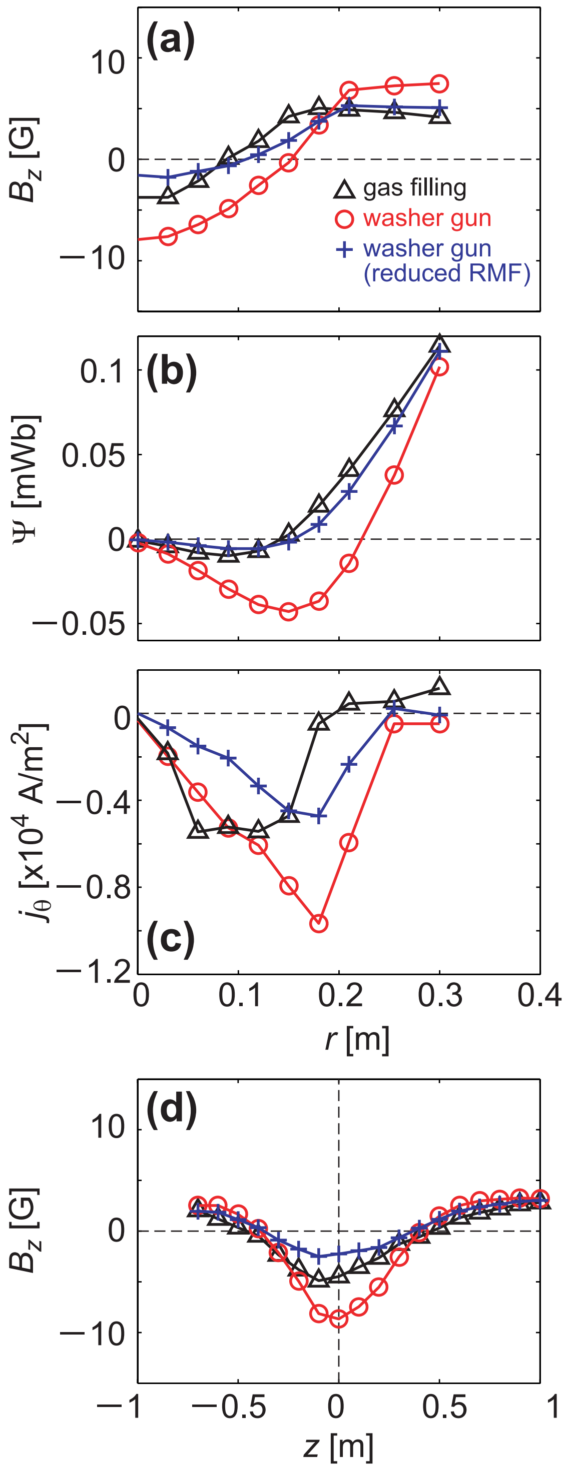


Fig. 5 Radial profiles of (a) steady axial magnetic field, (b) poloidal flux, and (c) azimuthal current density measured or calculated on the midplane ($z = 0$). The axial profile of the steady axial magnetic field along the geometric axis ($r = 0$) is shown in (d). The triangle and circle marks correspond to the discharges with the gas filling and washer-gun methods, respectively. The RMF currents in both cases are 700 A. The cross marks correspond to the discharge with the washer gun for a reduced RMF current of 400 A.

along the geometric axis ($r = 0$) is shown in Fig. 5 (d). The separatrix length $l_s$ for the FRC plasmas was almost same between the washer-gun and gas filling methods. It was considered that the plasma length was limited by the antenna length (1.2 m) in the present conditions; therefore, the neutral density influenced the azimuthal and radial force balances of the FRC equilibrium, without changing the axial distribution. The current drive efficiency $I_{\mathrm{plsama}}/I_{\mathrm{RMF}}$, where $I_{\mathrm{plasma}}$ is defined as $I_{\mathrm{plasma}} = \int j_\theta \mathrm{d}r\mathrm{d}z \sim l_s \int j_\theta \mathrm{d}r$, was equal to 1.42 and 1.12 for the washer-gun method with $I_{\mathrm{RMF}} = 700\mathrm{A}$ and 400 A, respectively, and equal to 0.75 for the gas filling case with $I_{\mathrm{RMF}} = 700\mathrm{A}$.

## 4. Discussion

The azimuthal force balance of the RMF current drive is expressed as follows [12]:

$$\nu\, m_e n_e \omega_e r = \left\langle \tilde{j}_z \tilde{B}_r \right\rangle, \quad (1)$$

where $\nu$ is the electron collision frequency and the bracket $\langle\,\rangle$ indicates average over an RMF cycle. The left-hand side of equation (1) represents the frictional force due to electron–ion and electron–neutral collisions, which must balance the RMF drive force at every radial position. The difference in the neutral density affects the collision frequency. In the present conditions, the electron–ion collision frequency $\nu_{\mathrm{ei}}$ is about 5 MHz, and the electron–neutral collision frequency $\nu_{\mathrm{en}}$ is estimated to be about 40 kHz in case of the washer-gun method. On the other hand, the gas filling method has a $\nu_{\mathrm{en}}$ of about 1.25 MHz when assuming uniform neutral density. Thus, the neutral density in the gas filling method is considered to be large enough to cause significant degradation of the RMF current drive.

One possible explanation is that the large azimuthal frictional force in the high neutral density case requires an equivalent RMF torque of $\left\langle \tilde{j}_z \tilde{B}_r \right\rangle$; however, the existence of the axial oscillating current $\tilde{j}_z$ inside the separatrix involves shielding of the RMF at that position, possibly resulting in partial penetration of the RMF [4, 5, 10]. If the penetration length becomes shorter than the separatrix radius, the drive torque of the azimuthal current will decrease near the geometric axis, i.e., reduction of the expanding magnetic force inside the field null will occur. As a result, the plasma will shrink, and an equilibrium with a short separatrix radius limited to the penetration length will be obtained in the high neutral density case. This interpretation is consistent with the experimental observation that the plasma current in the gas filling method flowed in the narrower region near the geometric axis than the washer-gun case, as shown in Fig. 5 (c).

Another important issue associated with the neutral density in the FRC driven by the RMF is ion spin-up due to electron drag [3, 7]. Since the RMF frequency $\omega_{\mathrm{RMF}}$ is set as $\omega_{\mathrm{ci}} << \omega_{\mathrm{RMF}} << \omega_{\mathrm{ce}}$ ($\omega_{\mathrm{ci}}$ and $\omega_{\mathrm{ce}}$ are ion and electron gyro frequencies, respectively), the RMF drives only the electrons. However, it is obvious that the Coulomb collisions between electrons and ions accelerate the ions in the azimuthal direction, leading to degradation of the current drive efficiency. A high neutral density is expected to suppress the ion spin-up in the FRC plasma maintained by the RMF [2–4, 7]. In the present experimental conditions, a slight decrease of the field reversal was observed in the FRC with the lower neutral density case, as shown in Fig. 3 (b); however, it did not cause any significant effect on the plasma behavior. The detailed mechanism of the ion spin-up and its suppression will be discussed in a subsequent paper.

## 5. Conclusions

The effects of neutral density on FRC equilibrium were investigated using a quasi-steady current driven by an RMF with higher harmonics. Lower neutral density yielded a higher current drive efficiency with full penetration of the RMF. On the other hand, a plasma current in the higher neutral density case flowed in a narrower region near the geometric axis than in the lower neutral density case, and the FRC equilibrium had lower current drive efficiency possibly due to the shorter penetration length of the RMF.


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