Drift Motion of Field-Reversed-Configuration Plasma across a Curved Magnetic Field

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We report the first observation of the behavior of a field-reversed-configuration (FRC) plasma translated into a curved magnetic field $\mathbf{B}_{\rm cur}$. The FRC shows a unique behavior in $\mathbf{B}_{\rm cur}$. The plasma splits into two parts: one is a bulk plasma confined in a field-reversed magnetic geometry, deflecting strongly across $\mathbf{B}_{\rm cur}$ despite β_E (the ratio of directed to transverse magnetic-field energy density) $\gg$1; the other is probably a peripheral plasma outside the separatrix, propagating rigidly along $\mathbf{B}_{\rm cur}$. This motion of the FRC may be due to $\mathbf{E} \times \mathbf{B}$ drifting, rather than displacement of the vacuum field by diamagnetic currents. [S0031-9007(97)02700-2]

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There are many experimental, theoretical, and computer studies of cross-field plasma propagation in several research areas such as the penetration of solar wind into the geomagnetic field [1], active releases of plasma in the magnetosphere [2], laser-plasma expansion against a magnetic field [3], plasma-beam injection into a magnetic containment device [4,5], and, recently, plasma heating in tokamaks by injecting an intense plasma beam [6] or spheromak [7] in the high-beta limit ($\beta_E \equiv$ plasma directed energy density/transverse magnetic field energy density > 1). Generally, the magnetic field does not restrict the plasma motion. In the $\beta_E \gg 1$ limit, for the case of the plasma beam that is not confined inside closed magnetic flux lines, the magnetic field is pushed aside, stretched, or squeezed by the plasma beam until the field has diffused. Then the field penetrating into the plasma deflects positive and negative species in opposite directions causing a transverse polarization electric field, which allows the plasma beam to continue an undeflected $\mathbf{E} \times \mathbf{B}$ motion across the magnetic field. However, the plasma moves along the magnetic field when the polarization electric field is short-circuited by some depolarization current [8]. On the other hand, for the case of the plasma with closed flux lines, there are as yet no experiments except for the spheromak-tokamak interaction [9].

A field-reversed-configuration (FRC) plasma [10] is one of the compact toroids, with $\langle\beta\rangle \sim 0.9$, where $\langle\beta\rangle$ is the volume averaged plasma beta. Here β is defined as the ratio of the local plasma pressure to the external magnetic field pressure. Most of the plasma is confined inside the separatrix of the field-reversed magnetic geometry by only a poloidal magnetic field B_p. This field B_p is generated by a plasma diamagnetic current that flows exclusively in the toroidal direction. An externally applied vacuum magnetic field insulates the FRC from a chamber wall.

We report the first observation of the behavior of the FRC injected into a curved magnetic field. The values of β_E are about 50, thus the so-called high-beta regime in beam propagation studies [4]. The translated FRC splits into two parts in the curved magnetic field. One is a bulk plasma confined in the field-reversed magnetic geometry. This bulk of the FRC does not go straight, but strongly deflects into the direction "*opposite*" to the bend of the curved magnetic field despite $\beta_E \gg 1$. The other is a plasma without B_p reversal, propagating along the curved field lines. Another feature of experiments is that for a plasma beam having no closed flux lines in the same apparatus, the plasma beam does not also continue an undeflected straight motion, but travels rigidly along the curved field lines. This implies that the polarization electric field which should be established inside the plasma beam has been short-circuited by some depolarization current. These results, therefore, suggest that no polarization electric field may be short-circuited inside the separatrix of the FRC, even when the field outside the separatrix is short-circuited.

Data are obtained in the FRC Injection Experiment (FIX) machine. A detailed explanation of the machine is described in Ref. [11]. The FRC plasma is formed in the theta pinch (at $t = 50\ \mu$s) and continuously translated inside the adjoining metal chamber with axial velocity v_z of about 10^5 m/s. Then the translated FRC passes through the midplane ($z = 3.4$ m) at $t \sim 80\ \mu$s. Plasma density $\overline{n}$ and pressure balance temperature $T_e + T_i$ of the translated FRC in this region are $\overline{n} \sim 7.0 \times 10^{19}$ m^{-3} and $T_e + T_i \sim 60$ eV, respectively. A pair of saddle shaped transverse field B_x coils, 0.6 m wide and 0.6 m long, is installed at each side of the metal chamber, 0.5 m upstream ($z = 2.9$ m) from the midplane. The axial guide field B_z applied here is produced by a solenoid that has a 1.04 m inner diameter. The strength of B_z, being uniform over the length of 3 m, is fixed to -400 G in these experiments. Figure 1 shows a schematic drawing of curved magnetic field lines in the vacuum in the case where B_z and B_x are -400 and 70 G, respectively. An array of 10 quartz tubes (6 mm o.d.), each of which contains 10 magnetic probes, is located at 0.2 m downstream ($z = 3.1$ m) from the center of the B_x coils. Each probe in a quartz tube is spaced every

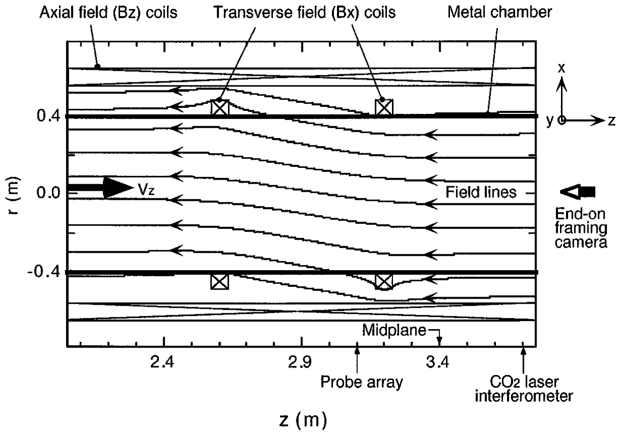

FIG. 1. Schematic drawing of a curved magnetic field in the FIX for $B_z \sim -400$ G and $B_x \sim 70$ G case. The solid lines show curved magnetic field lines. Note that the direction of B_z is opposite to that of z axis.

4 cm, which measures one field component on a given discharge. These 10 tubes are suspended with an interval of 4 cm, parallel to the y axis, except for the middle of the array where two probes are spaced 8 cm apart.

Substantial deflection of the translated FRC is observed when B_x is applied. This is illustrated in Fig. 2, which shows end-on 2D contours of B_p on three different B_x conditions: $B_x = 0, 70$, and -70 G. Values of B_p are time averaged for 10 μs. For the case of $B_x = 0$ G shown in Fig. 2(b), strong B_p reversal appears near the machine axis where $(x, y) \sim (-0.06, 0)$. Assuming that the translated FRC is entirely cylindrical (dashed circle), one estimates the separatrix radius r_s to be about 18 cm, which is approximately consistent with the value of the excluded flux radius $r_{\Delta\phi}$; $r_{\Delta\phi}$ is calculated to be 16 cm [11]. One notes that the translated FRC shifts slightly to the negative side of the x axis, which has always been observed in the FIX translation experiments [12]. The reason of this shift remains unknown, but probably by possible asymmetry of the solenoidal fields. One notes for the case of $B_x = 70$ G [Fig. 2(c)] that the strong B_p reversal considerably deflects to the right-hand side. For the $B_x = -70$ G case [Fig. 2(a)], on the other hand, the signal of B_p deflects to the left-hand side. As seen from the schematic drawing of field lines shown in Fig. 1, such deflected direction of the translated FRC is the opposite in which the field is curved. In other words, the translated FRC positively propagates across the curved field, and never goes straight. The values of the opposite deflection are evaluated to be about 15 cm for the $B_x = \pm 70$ G cases. This opposite deflection of the translated FRC was promoted more in applying stronger B_x to the plasma, plasma crashing into the vacuum chamber wall was observed as the most violent case, although the value of β_E was still greater than unity: $\beta_E \sim 5$. As seen from the data plotted in Figs. 2(a) and 2(c), the observed B_p signals in the curved region are no longer axisymmetric. These extend horizontally, which may indicate that the FRC expands to the direction of the transverse magnetic field.

In a series of experiments, a plasma beam having no closed flux lines (named "non-FRC plasma") is also translated into the curved magnetic field. The non-FRC is produced with the same procedure as the FRC except that the negative bias field is not applied at the formation phase. Considerable distinction of the motion between the non-FRC and the FRC is clearly visible in the series of para-axial, end-on framing pictures shown in Fig. 3. One notes from the photographs between $t = 85$ μs and $t = 105$ μs in Fig. 3(a) the bulk of non-FRC (white parts in those pictures) certainly moves to the left-hand side, and then impacts against the chamber wall. In other words, the non-FRC travels rigidly along the curved magnetic field, which is entirely contrary to the result of the FRC.

One notes from Fig. 3(b) for the case of the FRC that two distinct plasmas are recognized between $t = 75$ μs and $t = 105$ μs. Magnetic probe signals at the same shot revealed that the plasma on the right-hand side retained

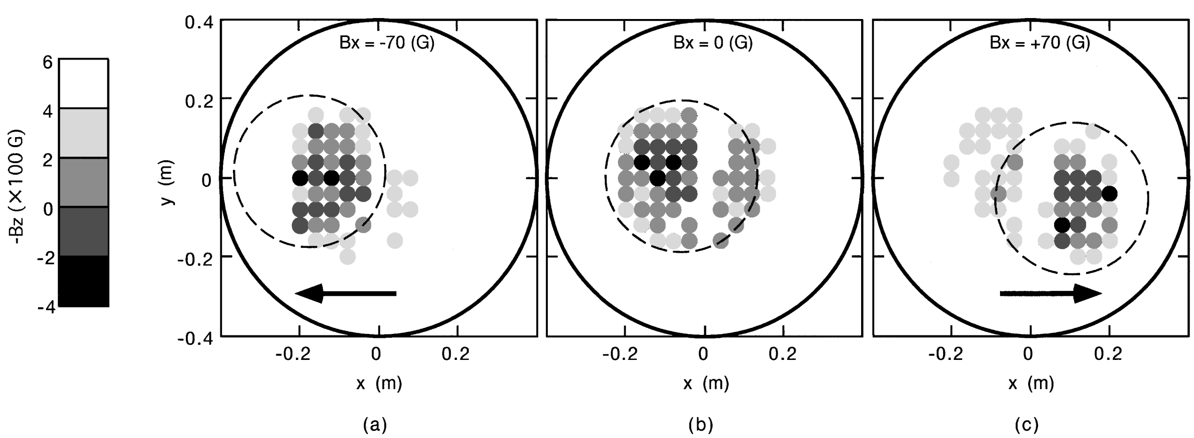

FIG. 2. Contour plots of $-B_z$ for $z = 3.1$ m at (a) $B_x = -70$ G, (b) $B_x = 0$ G, and (c) $B_x = 70$ G cases. Dashed circles show an approximate separatrix shape for no B_x case.

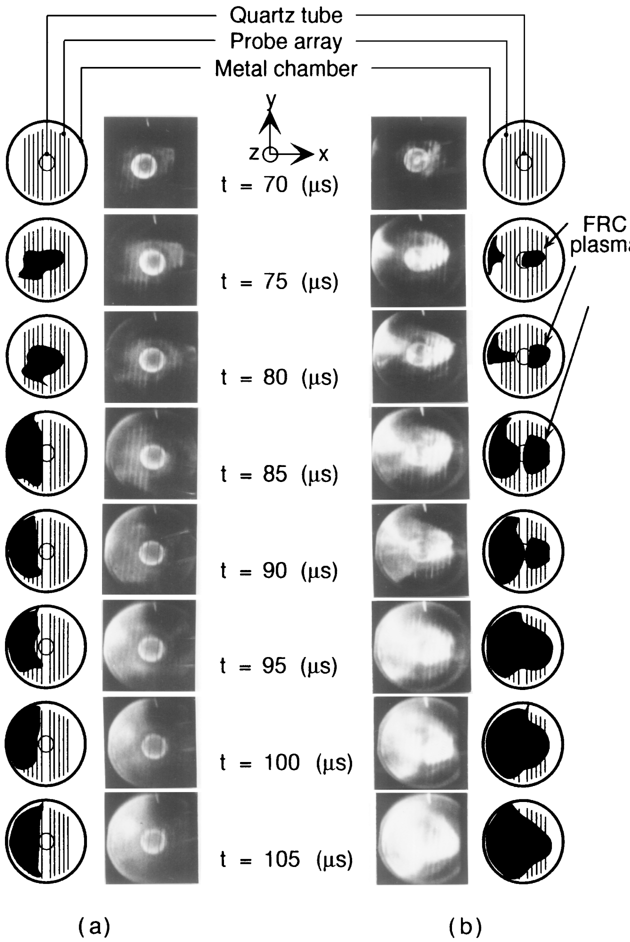

FIG. 3. Typical para-axial, end-on framing photographs for $B_x = 80$ G case of (a) non-FRC plasma and (b) FRC plasma.

strong B_p reversal. On the other hand, the other plasma on the left-hand side had no reversed field, in other words, had no closed flux lines. From the facts described above, we conclude that the plasma on the left is separated from the bulk of FRC and then travels rigidly along the curved field lines in just the same way as the non-FRC plasma shown in Fig. 3(a). Data similar to such splitting behavior in Fig. 3(b) were also obtained when B_x was negative. In those experiments, the bulk of FRC and the separated plasma from the bulk deflected to the left- and the right-hand side of the machine axis, respectively.

The above behavior of the non-FRC plasma has probably been caused through the short-circuiting of the polarization electric field [8]. Support for this conclusion comes from the plasma parameters listed in Table I. The value of β_E of the non-FRC plasma is also much greater than unity ($\beta_E \sim 35$), moreover, both values of the dielectric constant ϵ and the plasma density n also satisfy each critical value to produce a sufficient polarization electric field inside the plasma beam; the requirement in our experiments is that $\epsilon \gg (m_i/m_e)^{1/2} \sim 60$ [13] or $n \gg \{(m_i/m_e)^{1/2} - 1\}\epsilon_0 v_z B_x / e\rho_i^* \sim 7.7 \times 10^{12}$ m^{-3} [14], where m_i, m_e, ϵ_0, and ρ_i^* are ion mass, electron mass, dielectric constant

TABLE I. Nominal plasma parameters on the FIX. ω_i and Ω_i are the ion plasma frequency and gyrofrequency, respectively. Parameters computed for $B_x = 70$ G and the non-FRC plasma: $T_e + T_i = 20$ eV.

	FRC plasma	non-FRC plasma
Configuration	Closed field	Opened field
Plasma species	D^+	D^+
$n \sim \overline{n}_e \sim \overline{n}_i$ (m^{-3})	$\sim 7.0 \times 10^{19}$	$> 9.0 \times 10^{18}$
v_z (m/s)	$\sim 1.2 \times 10^5$	$\sim 1.3 \times 10^5$
$\beta_E[\equiv \frac{1}{2}\rho v_z^2/(B_x^2/2\mu_0)]$	~ 50	~ 35
$\varepsilon[\equiv 1 + (\frac{\omega_i}{\Omega_i})^2]$	$\sim 5.2 \times 10^6$	$\sim 5.6 \times 10^5$

for vacuum, and ion Larmour radius defined as $\rho_i^* = v_z/\Omega_i (= m_i v_z / eB_x)$, respectively. Therefore it was expected that the non-FRC plasma continued undeflected straight motion due to either $\mathbf{E} \times \mathbf{B}$ drift or displacement of the vacuum field by diamagnetic currents [5] or, at the most, deflected to the opposite direction in which the field was curved due to secondary $\mathbf{E} \times \mathbf{B}$ drift [5]. However, the non-FRC plasma certainly keeps on the curved field lines and then impacts against the vacuum chamber wall. This indicates the existence of some short-circuiting mechanism for the non-FRC plasma. Although several paths, along which the depolarization current flows [8], can be considered, widely-known end-shorting in a theta pinch [15] may give a reasonable explanation, since a sufficient $\int n_e dl$ signal has been observed in the theta pinch even when the bulk of translated FRC has reached the curved field region.

The result for the non-FRC plasma propagating rigidly along the curved field lines suggests that, in the FRC plasma case, the expected polarization electric field outside the separatrix has been short-circuited. Inside the separatrix, on the other hand, the polarization electric field may have been established and not short-circuited. This can be supported by the fact that the translated FRC deflects strongly to the opposite direction, in which the magnetic field is curved, and such an opposite deflection has been promoted more in applying stronger B_x to the plasma. In other words, substantial longitudinal velocity v_x across the curved field has originated inside the FRC injecting into there. If this cross-field propagation of the FRC is due to displacement of the vacuum field by diamagnetic currents, the plasma should either go straight, because the value of β_E is much greater than unity and the transit time Δt for the FRC through the curved region is about 4 μs too short to deflect so strongly, or propagate along curved magnetic field lines. Therefore the produced polarization electric field and the poloidal field of the FRC may have caused the plasma to $\mathbf{E} \times \mathbf{B}$ drift across the curved magnetic field.

The above possibility of the existence of the polarization electric field can be provided by the measured magnetic field profiles of $B_z(y)$ and $B_x(y)$ shown in Fig. 4. These are measured simultaneously for the case

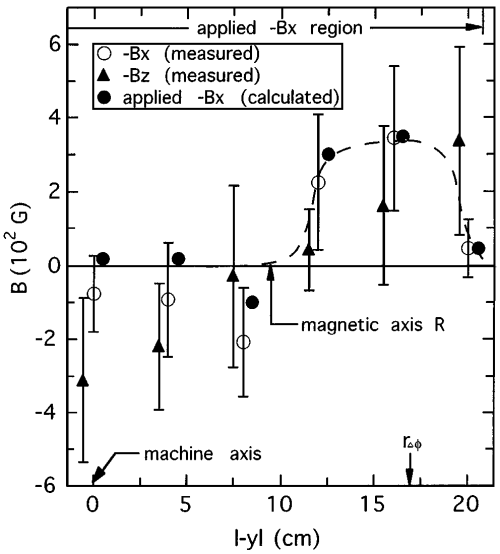

FIG. 4. Averaged central FRC magnetic field profiles along $x = -8$ cm for $B_z(y)$ and $x = -12$ cm for $B_x(y) = -70$ G case. Plotted data are average values of three shots.

of $B_x = -70$ G, and the fields are time averaged for 10 μs for the bulk of FRC at each location. Since all values of $B_x(y)$ involve the components for both B_p due to deflection and stray fields due to possibly toroidal fields B_t observed in a translated FRC [12,16], the profile of the applied B_x (dashed line) is obtained by subtracting [17] approximate values of the x component of both B_p and B_t. One notes from Fig. 4 that values of applied B_x decrease rapidly from $|B_x| \sim 300$ to $\sim$70 G near the location of $y = -12$ cm and are almost zero inside the magnetic axis $[B_z(R) = 0]$. Since $B_x = -70$ G in vacuum, this indicates that the applied B_x could not penetrate deeply inside the magnetic axis, but localize in the region between the magnetic axis and the separatrix. Such shallow penetration of the applied B_x could allow the transverse polarization electric field $E_y = -v_z B_x$ to establish only in the region outside the magnetic axis. This field E_y is electrostatic so that it propagates to the region inside the magnetic axis between the magnetic axis and the symmetry axis of the FRC along closed magnetic field lines, and, consequently, $-E_y$ could also appear in B_p reversed regions where the applied B_x has not penetrated. This is because the electric potential associated with the electrostatic component of the electric field must be constant along magnetic field lines, since the electron thermal speed is much greater than the propagation velocity of the FRC. Therefore both $E_y \times B_p$ drifting outside the magnetic axis and $(-E_y) \times (-B_p)$ drifting inside the magnetic axis may cause the bulk of FRC to have a transverse drift across the curved magnetic field.

The penetration depth, however, is still much greater than the classical skin depth δ. Assuming $\delta \sim (2\eta\Delta t/\pi\mu_0)^{1/2}$, where η is Spitzer's resistivity [18], one estimates $\delta \sim 0.17$ cm for $\eta/\mu_0 \sim 1.1$ m^2/s and $\Delta t = 4$ μs. For the non-FRC plasma, on the other hand, almost equal value of δ is also obtained from the data: $\delta \sim 0.37$ cm for $\eta/\mu_0 \sim 5.4$ m^2/s. Nevertheless, for this case the applied B_x has penetrated deeply inside the bulk of non-FRC, which is similar to those observed in intense ion beam experiments [19]. The difference, therefore, may be attributed to whether the magnetic field configuration is closed or not.

In summary, FRC plasma formed in a theta pinch is, for the first time, translated into the curved magnetic field. The translated FRC splits into two parts, and the bulk of FRC having B_p reversal deflects strongly across the curved magnetic field. Although the data suggest $\mathbf{E} \times \mathbf{B}$ drifting as a possible mechanism, theoretical modeling is required to conclude it confidently.

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[17] Measured $B_x(y)$ is approximated by $B_x(y) \sim B_x(\text{applied}) + B_p \sin\theta + B_t \cos\theta$, where θ is the deflection angle of the translated FRC; B_t is provided by another shot where no B_x has been applied. Since $B_t(0) \sim 0$, we can evaluate θ and B_p as $\theta \sim \tan^{-1}[B_x(0)/B_z(0)]$ and $B_p \sim B_z \sec\theta$, respectively.
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