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FRC FORMATION EXPERIMENTS WITH TEARING RECONNECTION ON THE FRX-C/LSM DEVICE

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ABSTRACT

Field-reversed configuration (FRC) formation studies performed on the FRX-C/LSM device during February and March 1986 are documented. Experiments were restricted to the tearing-reconnection mode of formation at 10 mtorr deuterium fill pressure. Magnetic tearing was driven with 0.3-m-long, 0.66-m-id passive end mirrors mounted on a θ -pinch coil with a 1.4-m-long, 0.76-m-id central section. Typical plasma densities and temperatures were $\bar{n} \simeq 2 \times 10^{15} \text{ cm}^{-3}$ and $200 \leq T_e + T_i \leq 450 \text{ eV}$, respectively. Two parameters were varied: the magnitude of the reversed-bias B-field, $0.5 \leq B_b \leq 1.4 \text{ kG}$, and the time interval $\Delta\tau_{PI}$ (set at either 5, 12, or 30 μs) between preionization and the initiation of the main discharge. As B_b was increased the axial shock and radial swelling after reconnection became stronger with transient plasma elongations decreasing from 3 to 1. The inferred trapped poloidal flux Φ_p increased with B_b , while at a given B_b , the maximum Φ_p was obtained at the shortest $\Delta\tau_{PI}$. The normalized separatrix radius x_s at the start of the equilibrium phase varied from 0.35 to 0.65 and Φ_p ranged between 2 and 20 mWb. This upper value of Φ_p is about 4-times larger than that achieved in FRX-C with a 0.5-m-id coil; however, the longest flux confinement times, $\tau_\Phi \leq 100\mu\text{s}$, were obtained only at small Φ_p .

I. Introduction and Summary

The formation of field-reversed configuration (FRC) compact toroid plasmas has been the subject of many recent experimental¹⁻⁴ and theoretical⁵⁻⁹ programs. FRC formation with the tearing-reconnection mode of operation has been studied recently in the FRX-C device at Los Alamos,^{10,11} and several important features have been found. For example, as the magnitude of the reversed-bias field B_b was increased, more severe axial contractions occurred after magnetic reconnection. Poor confinement of the inferred trapped poloidal flux Φ_p was observed whenever the minimum plasma elongation ϵ_{min} during formation fell below a threshold of about three.¹⁰

The purpose of this Report is to document similar experimental FRC formation studies performed on the larger FRX-C/LSM device during February and March 1986. The organization of this paper is as follows: In Sec. II the FRX-C/LSM hardware and the experimental conditions are described. Experiments have been restricted to a 10-mtorr, deuterium initial fill pressure while two parameters, B_b and $\Delta\tau_{PI}$, the time interval between preionization (PI) and initiation of the main capacitor bank, were varied. The PI conditions are reviewed in Sec. III. The main bank is discharged with PI integral density profiles that can be peaked at the ends, relatively uniform, or peaked near the center of the θ -pinch coil. FRC formation is reported in Sec. IV. As B_b is increased from 0.55 to 1.4 kG stronger axial contractions are observed, while Φ_p increases from 2 to 20 mWb. ϵ_{min} is usually less than 3 for all conditions.

Observations made during the FRC equilibrium phase are reported in Sec. V. Larger-radii (or Φ_p) plasmas appear more hollow. Almost every FRC equilibrium extends axially such that interactions with the end-mirrors are probably non-negligible.

A preliminary report on the flux confinement is found in Sec. VI. Best confinement ($\tau_\Phi > 100\mu\text{sec}$) is found at low B_b and with uniform axial profiles of the PI density. Confinement is clearly degraded at the conditions which result in the largest Φ_p ; however, it is unclear whether this degradation is either due to the formation asymmetries associated with tearing reconnection or due to instabilities which appear at large Φ_p .

II. Experimental Conditions

Experiments have been performed on the FRX-C/LSM device, a field-reversed θ -pinch experiment located at Los Alamos. The experimental mission and the design details of FRX-C/LSM are reviewed elsewhere.^{12,13} The data reported in this paper have been obtained with a θ -pinch coil consisting of a 1.4-m-long, 0.76-m-diam straight section with 0.3-m-long, 0.66-m-diam passive end mirrors. Typical vacuum magnetic flux surfaces and a field profile are illustrated in Fig. 1. Experiments have been restricted to the following conditions: (1) an initial deuterium fill pressure of 10 mtorr; (2) a θ -pinch preionization bank charge voltage of 45 kV (corresponding to a vacuum peak-to-peak B -field modulation of 1.6 kG at the axial midplane; (3) use of a 10-MHz rf pre-preionization. The rf system consists of a 1.2-ms-long, 3-kW pulse transmitted from antennas mounted at each end of the θ -pinch coil on the outside of the 0.6-m-diam quartz vacuum chamber. Two parameters have been varied in these experiments: (1) the magnitude B_b of the reversed-bias magnetic field; and (2) the time interval $\Delta\tau_{PI}$ between the discharging of the θ -pinch preionization and the main capacitor banks. Bias scans with $0.5 < B_b < 1.4$ kG have been performed with $\Delta\tau_{PI}$ fixed at either 5, 12, or 30 μ s. The corresponding Green-Newton bias field¹⁴ at 10 mtorr is 2.1 kG.

The two principal plasma diagnostics are an excluded flux array consisting of an external flux loop and twelve magnetic probes and a six-chord HeNe-laser interferometer system. The interferometers view the plasma side-on and they are configured either axially at positions $z = 0.0, \pm 0.4, +0.6, \pm 0.8$ m (where $z = 0$ is the axial midplane) or radially at $z = 0$ and impact parameters $b = 0, 0.06, 0.09, 0.12, 0.15, 0.17$ m.

Typical FRC plasma parameters obtained are: $n_e \simeq 2 \times 10^{15} \text{cm}^{-3}$, $T_e + T_i = 200 \rightarrow 450$ eV, $B_w = 4 \rightarrow 6$ kG, $x_s = 0.4 \rightarrow 0.6$.

III. Preionization

The preionization (PI) of the 10-mtorr- D_2 fill has been characterized with the excluded flux and interferometer arrays. The magnetic data are incomplete since the internal B -field is not measured. Internal measure-

ments are needed to infer the movement of a plasma sheath during a PI discharge;¹⁵ however, the external measurements discussed below provide useful information. Typical signals from the center interferometer chord ($b = 0, z = 0$) are illustrated with the corresponding excluded flux data in Figs. 2 and 3 for PI discharges at low ($B_b \simeq 0.7$ kG) and moderate ($B_b \simeq 1.15$ kG) bias strengths, respectively. In these figures the time $t = 0$ corresponds to the discharging of the θ -pinch PI capacitor bank.

The time of the initial gas breakdown depends on B_b . From the data in Figs. 2 and 3 this breakdown is first detected by the initial appearance of excluded flux $\Delta\Phi$. The integral density at this time is usually too small to observe with the interferometers. At low bias (Fig. 4) breakdown occurs at time $t \simeq 1.8\mu\text{s}$, at about the time of the second zero-crossing when $B \ll B_b$ and E_θ is at about half-maximum. At the largest bias (Fig. 4), breakdown occurs at larger fields, $B \geq B_b$. Evidently, there appears to exist a transition field $B_b \approx 1.1$ kG, (somewhat above the zero-crossing field of $B_b = 0.8$ kG) above which initial breakdown occurs near the applied bias level. The magnitude and spatial dependence of the integral density early in time vary with the bias strength. At lower bias, $B_b < 1.1$ kG, a measurable plasma density first appears at time $t \simeq 4\mu\text{s}$ near the ends of the θ -pinch coil. These end plasmas are radially compressed by time $t \simeq 5\mu\text{s}$. The midplane plasma is compressed radially a couple of microseconds later. Sample $\int n dl$ profiles are illustrated in Figs. 5 and 6 for the $B_b \simeq 0.7$ kG case. The plasma at the axial midplane does not undergo a second radial compression even though the B-field oscillates a complete cycle between $t = 10$ and $15\mu\text{s}$. Density waves do, however, propagate axially toward the midplane between $t = 15$ and $20\mu\text{s}$ which results in a second, more modest radial compression or plasma accumulation at the center. The axial $\int n dl$ profile remains peaked until after $t = 30\mu\text{s}$. As B_b is increased from 0.6 to 1.0 kG the initial axial profile becomes less peaked while the initial radial compression at the midplane and subsequent axial density waves become less pronounced.

At higher bias, $B_b \geq 1.1$ kG the integral density profile at the midplane is relatively uniform for all times (Fig. 7). The axial profile (Fig. 8) is also more uniform early in time but becomes peaked after weak density waves reach the center at $t = 22\mu\text{s}$. At the highest bias, $B_b \geq 1.25$, the profiles

remain relatively uniform but the degree of ionization is further reduced and varies from discharge-to-discharge.

The Milroy-Brackbill 2-D MHD¹⁶ code has been used to model the preionization plasma. The initial conditions for the simulations are very idealized. The plasma is assumed to be fully ionized and uniform over the tube cross section. The initial density is assumed to decrease linearly with the axial distance outside the coil. The calculation starts 2.2 μ s after the preionization bank is fired; this is approximately the time when the observed excluded flux signal becomes significant (see Fig. 2). The flux in the coil is approximated by:

$$\Phi(t) = \pi r^2 B_b + \pi r^2 B_{PI} \sin 2\pi f(t - t_o) e^{-(t-t_o)/\tau}$$

where r is the radius of the coil, B_b is the bias field (0.8 kG in the central section), B_{PI} is the initial amplitude of the preionization magnetic field (1.0 kG), f is the frequency of the preionization field (170 KHz), t_o is the breakdown time (2.2 μ sec) and τ is the decay time constant of the preionization waveform (6.0 μ sec). The purpose of these calculations is to show the qualitative features of the preionization plasma. No attempt has been made to vary the simulation parameters so that the calculation results are in quantitative agreement with the experimental observations. Figure 9a shows the velocity vectors and the flux contours in the upper left quadrant for $t = 3.2, 4.2, 6.2, 8.2, 10.2, 12.2$ and 14.2μ s. It is seen that the oscillating field excited a compressional wave which propagates approximately in the radial direction. Both the amplitude and propagation velocity of this wave are larger under the passive mirror region than in the central section. The wave motion is a mixture of the natural oscillation of the plasma column in response to the early large amplitude perturbation and a fast decaying forced oscillation. The complexity of this motion leads to continuous variation of the flow patterns. Note also the gradual increase of the directed axial flow outside the coil. Figure 9b shows the variation of the line density and $\int n dl$ for $t = 3.2, 4.2, 6.2, 8.2, 10.2, 12.2$, and 14.2μ sec. Note that $\int n dl$ as measured by a side-on, two-pass interferometer equals $4 \int_0^R n(r) dr$. It is seen that the line density under the mirror section decreases steadily as the plasma is evacuated from this region. $\int n dl$ exhibits larger variations as the plasma experiences radial oscillations which have

different phases at different axial locations because $\int n dl$ depends on the radial density distribution.

IV. FRC Formation

The formation of the FRC equilibrium is accomplished using almost the same sequence as that used in earlier experiments on FRX-C¹⁰: (1) application of reversed bias field; (2) rf pre-preionization; (3) ringing- θ -pinch preionization; (4) discharge of the main capacitor bank which results in: (a) field-reversal and plasma lift-off from the wall; (b) radial compression; (c) magnetic reconnection at the ends and axial contraction. This sequence is revealed by the magnetic and interferometric data in Figs. 10-13 for typical discharges with $B_b \simeq 0.7$ kG and $\Delta\tau_{PI} \simeq 12\mu s$. (The best flux confinement to date has been obtained at these conditions - see Sec. VI.) For these data, the main bank is discharged at $t = 0$. The “lift-off” B-field is estimated with the “zero-crossing” field, $B_{zc} \simeq \Phi(B = 0)/\pi r_t^2$, where r_t is the vacuum chamber wall radius and $\Phi(B = 0)$ is the flux measured at the instant the external B-field crosses zero. As illustrated in Fig. 14, B_{zc} increases with B_b and depends on $\Delta\tau_{PI}$. The zero-crossing field increases nonlinearly with the bias strength. At a given B_b there is little change in B_{zc} at the two early PI timings, $\Delta\tau_{PI} = 12$ or $30\mu s$; however, the zero-crossing field is clearly larger at delayed PI, $\Delta\tau_{PI} \simeq 5\mu s$. As B_b is increased from 0.6 to 1.3 kG, the ratio of trapped to applied bias flux at reversal B_{zc}/B_b varies from 15% to 50% at early PI and 65% to 85% at delayed PI. It is unclear at this time on the cause of the B_{zc} increase at short $\Delta\tau_{PI}$. These observations might be attributed to smaller flux losses because of the short time interval. On the other hand, the B_{zc} increase might simply be due to the θ -pinch PI B-field augmenting B_b . For $\Delta\tau_{PI} \simeq 5\mu s$, the main bank is discharged during the second-half cycle of the PI waveform at a time when the external B-field is clearly greater than B_b . Internal B-field measurements are clearly warranted in future studies in order to resolve these observations.

The Fig. 11 and 12 data indicate that the plasma diamagnetism and integral density are peaked at the ends during the radial compression ($4 \leq t \leq 7\mu s$). The integral density profile contracts axially reaching its minimum length, $l_{min} \simeq 0.8$ m, at time $t \simeq 10\mu s$. (All lengths are inferred from full-

widths-at-half-maxima.) The contraction of the excluded flux profile, on the other hand, is hardly noticeable with $l_{\min}$ remaining greater than 1.2 m. After the peak contraction ($t > 10\mu\text{s}$) the plasma expands axially with the $\int n dl(z)$ profile taking the shape of $r_{\Delta\Phi}(z)$ by time $t = 20\mu\text{s}$. Combining the density and magnetic data, one can estimate the particle inventory N . At time $t = 15\mu\text{s}$, N is found to be 2.6×10^{20} which implies that approximately 70% of the initial D_2 fill inside the θ -pinch coil is swept-up during FRC formation.

At larger bias (Figs. 15-18), the formation dynamics are more pronounced. The integral density at axial positions $z = \pm 0.4$ m is often zero during the peak of the axial contraction. The excluded flux array also indicates stronger contractions although the corresponding $l_{\min}$ values remain consistently 50-100% larger than those inferred from interferometry (Fig. 19). This discrepancy cannot be explained by the failure of the excluded flux array to accurately infer short FRC lengths. Another noteworthy feature is the 2-4 μs delay between the density and excluded flux peak contractions. The observed stronger dynamics are illustrated in Figs. 20 and 21 in which maximum excluded flux radii $r_{\max}$, minimum lengths (from interferometry), and minimum elongations $\epsilon_{\min} = l_{\min}/2r_{\max}$ are plotted for a number of discharges obtained over the full range of B_b and $\Delta\tau_{PI}$. For a given graph, each data point corresponds to a separate discharge.

The poloidal flux Φ_p trapped within the FRC can be inferred from the excluded flux, provided one assumes the form of the FRC equilibrium. Φ_p is estimated beginning at time $t = 20\mu\text{s}$, after the formation dynamics subside. A typical, diffuse radial equilibrium profile is assumed (with the parameter ϵ defined in Eq. 14 in the paper by Spencer *et al.*,¹⁷ set equal to -0.25). The corresponding trapped flux can then be written as:

$$\Phi_p = B_w r_w^2 x_s^{3.25} \quad (1)$$

where B_w is the external B-field, r_w is the θ -pinch coil radius, x_s is the plasma separatrix radius normalized to r_w . The flux at time $t = 20\mu\text{s}$ is found to vary between 2 and 20 mWb (Fig. 22) with the largest values obtained at highest B_{zc} (*i.e.*, at highest bias and with $\Delta\tau_{PI} = 5\mu\text{s}$). The inferred Φ_p at $t = 20\mu\text{s}$ ranges between 30% and 80% of the magnetic flux at field reversal, $\pi r_t^2 B_{zc}$.

V. Equilibrium

The FRC equilibrium phase following formation begins at about time $t = 20 \mu\text{s}$. Radial equilibrium is maintained over an Alfvén transit time, $2r_s/v_A < 3\mu\text{s}$. The inferred radial profile of the integral density varies with Φ_p (or x_s) as shown by the data points in Figs. 23a and 24a for two typical discharges taken at low and high B_b , respectively. These data have been obtained near the start of the equilibrium phase. A “density hole” is evident at large x_s , indicative of a more peaked $n(r)$ profile. The dashed lines also plotted in Figs. 23a and 24a are best fits of these data computed assuming the usual¹⁸ equilibrium profile

$$n = \begin{cases} n_m \{1 - (1 - \beta_s) | \frac{2r^2}{r_s^2} - 1 |^\eta\} & r \leq r_s \\ \beta_s n_m \exp - \{ \frac{r^2 - r_s^2}{2r_s a} \} & r \geq r_s \end{cases} \quad (2)$$

where η is an integer between 2 and 5. The average beta condition, $\langle \beta \rangle = 1 - 1/2x_s^2$, implies that there is an additional constraint

$$\beta_s = 1 - (\eta + 1)x_s^2/2 \quad (3)$$

Therefore, the computer fits the six integral density measurements using only three parameters n_m , a , and η . The software accomplishes this by fitting the data with n_m and a for every η . The best fit (*i.e.*, minimum error) results in the final selection of η . The corresponding $n(r)/n_m$ profiles inferred from the data with Eqs. (2) and (3) are plotted in Figs. 23b and 24b.

At low x_s (*e.g.*, see Fig. 23) the inferred $n(r)$ profiles are somewhat flat ($\eta = 3$) and β_s is always large (≥ 0.7). The maximum density varies, $2 \times 10^{15} < n_m < 3 \times 10^{15} \text{cm}^{-3}$, depending on the time and discharge. The density scale length a outside the separatrix is best estimated later during a discharge when the two outermost interferometer chords view mainly the open-field-line plasma. The scale length varies from shot-to-shot between 0.7 and 2 cm, which corresponds to $2 \rightarrow 6$ ion gyroradii (assuming $T_i \simeq T_T/2 = 100 \text{ eV}$ and $B_w = 4 \text{ kG}$).

At high x_s (*e.g.*, see Fig. 24), $n(r)$ is more peaked near the field null ($\eta = 2$). β_s is modest initially (typically about 0.4) and it usually increases by 50% during the course of a discharge as x_s decreases. The density

scale length a cannot be accurately determined in this case since all of the interferometers view a substantial part of the closed-field-line region.

During the equilibrium phase the $\int n dl(z)$ and $r_{\Delta\Phi}(z)$ profiles appear somewhat similar (Figs. 25 and 26). The $n = 2$ rotational instability is evident at $t \geq 60\mu s$ in low- Φ_p , long-lived discharges. From the data in Figs. 25 and 26 one finds that the plasma extends into the mirror regions which begin at $z = \pm 71$ cm. One might, therefore, expect the mirror fields to affect $\langle\beta\rangle$, and, consequently, the inferred Φ_p . Changes in $\langle\beta\rangle$ due to the mirrors have been estimated using Eq. A3 in the paper by Spencer and Tuszewski.¹⁹ The FRX-C/LSM plasma separatrix profile is first crudely modeled as an 18-cm-radius cylinder ($x_s = 0.47$) of variable length with hemispherical ends. The computed $\langle\beta\rangle$ values are plotted in Fig. 27a for plasma lengths l_p (defined as the distance between x-points) ranging between 40 and 160 cm. Significant deviations in $\langle\beta\rangle$ from the expected $(1 - x_s^2/2)$ value are found for $l_p \geq 125$ cm. In the experiment, the profile $r_s(z)$ is clearly more elliptical; therefore, these rough estimates should be considered as upper bounds. Indeed, for elliptical separatrices, the computed $\langle\beta\rangle$ changes (Fig. 27b) are smaller, although they remain non-negligible for $l_p \geq 150$ cm. Changes in the inferred Φ_p caused by the mirrors will soon be calculated with 2-D MHD equilibrium computations.²⁰

VI. Flux Confinement

The FRC confinement properties during the equilibrium phase are briefly summarized in this section. We restrict our attention to flux confinement. Particle and energy loss information can be extracted from the data, if desired, in future work. The poloidal flux Φ_p is inferred from external flux measurements and an equilibrium model (see Sec. IV). While a particular Φ_p for a diffuse-profile equilibrium is given by Eq. 1, Φ_p values for all equilibria are bounded by two extrema, corresponding to the low and high-flux sharp boundary profiles,²¹

$$\Phi_{LF} = \frac{\pi x_s^2 r_s^2 B_w}{4} \quad (4)$$

$$\Phi_{HF} = \frac{\pi x_s}{2\sqrt{2}} r_s^2 B_w \quad (5)$$

The time history of Φ_p has been calculated from Eqs. (1) or (4)-(5) for every discharge. The decay of Φ_p for each discharge can be usually classified into one of four modes:

MODE 1: Best Φ_p confinement

MODE 2: Poor Φ_p confinement with relatively uniform decay rate

MODE 3: Poor Φ_p confinement with a faster decay initially

MODE 4: Poor Φ_p confinement with a slower decay initially

Examples of flux decay for each mode are illustrated in Fig. 28. Each graph corresponds to a separate discharge and contains three plots. The broken lines denote the extrema in Φ_p (Eqs. 4 and 5) while the solid lines indicate the flux for the diffuse equilibrium profile (Eq. 1). The relative frequencies of occurrence of these modes are displayed in the Fig. 29 histograms.

Mode 1 discharges are defined as those in which the exponential decay time $\tau_\Phi = -\Phi/(\frac{d\Phi}{dt})$ is greater than several axial Alfvén transit times, *i.e.*, $\tau_\Phi > 80 \mu s$. Mode 1 has been obtained only at $\Delta\tau_{PI} = 12 \mu s$ and $0.6 \leq B_b \leq 0.7$ kG. The zero crossing B-fields and the trapped flux at the start of the equilibrium phase are relatively small, always less than 0.3 kG and 6 mWb, respectively.

Mode 2 discharges are characterized by relatively fast, uniform flux decay, $\tau_\Phi \leq 30 \mu s$. Mode 2 has been observed at all bias fields with $\Delta\tau_{PI} = 30 \mu s$ and also at $B_b \leq 0.65$ kG or $B_b \geq 0.8$ kG with $\Delta\tau_{PI} = 5$ or $13 \mu s$. In Mode 3 discharges, τ_Φ is again short but the decay of flux is somewhat faster during the first 10 – 20 μs of the equilibrium phase. Mode 3 is obtained almost exclusively at higher bias, $B_b > 0.9$ kG on approximately 50% of the discharges.

Mode 4 discharges are characterized by intermediate confinement times initially, $\tau_\Phi \simeq 50 \mu s$, followed by a rapid loss in flux at later times $t > 30 \mu s$. The rapid flux loss is sometimes (but not always) accompanied by an axial shift of the excluded flux radius center of volume. Mode 4 is obtained primarily at $\Delta\tau_{PI} = 5 \mu s$ with modest bias fields $B_b = 0.65 \rightarrow 0.9$ kG.

VII. Discussion

In the FRX-C/LSM device, it has been demonstrated that the preionization and reversed bias field strengths clearly influence the FRC formation dynamics and the equilibrium confinement.

At low bias strengths the magnetic field inside the θ -pinch coil is initially reversed by the PI-bank discharge and the D_2 fill breaks down just after the second B-field zero-crossing. The breakdown begins at a time when B is smaller than the applied bias field B_b . Therefore, to maximize flux trapping, the applied bias must diffuse through the PI plasma. Internal magnetic field measurements are necessary to determine the amount of diffusion. Unfortunately, such measurements have not yet been attempted in FRX-C/LSM. There is, however, possible indirect evidence of fast field diffusion during the early stages of the PI. At $\Delta\tau_{PI} = 5\mu s$, the external B-field from the PI capacitor bank adds to the bias at the time when the main bank is discharged. The diffusion of this added bias might be responsible for the observed increased trapped flux at field reversal $\pi B_{zc}\tau_t^2$.

The PI plasma is clearly more dynamic at lower bias fields (Figs. 5 and 6). Radial compression and axial density waves are observed. At larger bias, breakdown occurs more gradually (Figs. 7 and 8) and the plasma appears stiffened by the larger fields. A transition field is found above which the radial and axial structure in PI plasma density becomes much less pronounced. This transition occurs at about 1.1 kG, a value considerably larger than the bias, $B_b = 0.8$ kG, at which the θ -pinch PI B-field grazes zero.

As the bias field strength is increased, more flux is trapped at each $\Delta\tau_{PI}$ setting (Fig. 22). The θ -pinch-PI breakdown occurs without zero crossing but usually not at the maximum E_θ . Larger bias results in more severe axial contractions and larger plasma radii during FRC formation as illustrated in Fig. 20. The decrease in minimum elongation ϵ_{min} with increased B_{zc} is in qualitative agreement with earlier experiments¹⁰ and theory.⁹ An interesting observation is that the plasma contraction is faster and stronger than that of the excluded flux profile (Fig. 18). Barring any unknown systematic errors in the measurements, this effect appears to imply non-negligible contributions of plasma inertia during formation.

Indeed, the MHD simulations with the Milroy-Brackbill code support this hypothesis. The simulations show that the minimum length ℓ_{min} as inferred from the density measurement is indeed shorter than that inferred from the excluded flux measurement. The results from a typical simulation are presented in Fig. 30 which shows the variation of the full-width-at-half-maximum FRC length as inferred using a) the excluded flux radius, b) the $\int n dl$ signal, and c) the line density. It is seen that the length estimated using the excluded flux radius is always larger than the length estimated from $\int n dl$ and from the line density. This is expected because only the outer flux surfaces extend axially to the FRC ends and the number density on these surfaces is smaller than that on the inner surfaces. Note that the length as estimated using the $\int n dl$ signal exhibits rapid oscillations for $t \leq 6 \mu s$. These oscillations are not caused by axial motion; they occur because the plasma undergoes radial oscillations with different frequencies at different axial locations. It also is seen from the figure that the discrepancy between FRC length as inferred from the excluded flux radius and from the $\int n dl$ signal is more apparent during the peak axial contraction when the area waves propagating from the FRC ends merge. Figure 31 shows the flux surfaces and the density contours at $t = 16 \mu s$. It is seen that the density is not constant along the field lines and that it increases towards the $z = 0$ plane.

In FRX-C/LSM, ϵ_{min} typically ranges between 1 and 3 (Fig. 21). Therefore, almost all of our data fall short of the threshold condition, $\epsilon_{min} \geq 3$, found necessary for good confinement in FRX-C experiments with the smaller coil and discharge tube.^{10,11} In FRX-C/LSM the best flux confinement to date ($\tau_\Phi = 100 \rightarrow 200 \mu s$) has been obtained at relatively low flux, $\Phi_p < 6 \text{ mWb}$, and largest minimum elongations $\epsilon_{min} \simeq 2.7$. For these plasmas the field null resistivity η (inferred assuming a rigid-rotor equilibrium with $T_e \simeq T_T/2 \simeq 100 \text{ eV}$) is at least ten times the classical value with $Z_{eff} = 1$. In earlier FRX-C discharges at similar T_e but with $\epsilon_{min} \geq 3$, the resistivity anomaly factor was about five for discharges with the best confinement.

FRC formation using the programmed-mode (*i.e.*, with no tearing reconnection) has been demonstrated to be superior^{1,3} in that the strong axial dynamics with $\epsilon_{min} < 3$ can be tolerated with no subsequent degradation

in confinement. In fact, it has been reported that τ_ϕ improves as Φ_p is increased.²² These observations lead one to anticipate that on upcoming programmed formation experiments on FRX-C/LSM, not only will the confinement improve at low bias but it will improve even further as B_b (and Φ_p) is increased.

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References

- ¹V. V. Belikov, V. M. Goloviznin, V. K. Korshunov, A. P. Kreshchuk, R. Kh. Kurtmullaev, Ya. N. Laukhin, A. I. Malyutin, A. P. Proshletsov, O. L. Rostovtsev, V. N. Semenov, and V. F. Strizhov. Suppression of losses in a compact torus with programmed shaping of the magnetic structure. In *Plasma Physics and Controlled Nuclear Fusion 1982*, page 343, IAEA, Vienna, 1983. Vol. II (Baltimore conference).
- ²W. T. Armstrong, D. G. Harding, E. A. Crawford, and A. L. Hoffman. Flux-trapping during formation of FRC's. *Physics of Fluids*, 25:2121, 1982.
- ³J. T. Slough, R. D. Milroy, D. G. Harding, and A. L. Hoffman. Experimental and numerical study of various methods of programmed formation. In *7th Compact Torus Symposium*, Los Alamos National Laboratory, Los Alamos, NM, 1985. To be published in proceedings of that meeting.
- ⁴C. Wu, Y. Aso, S. Himeno, S. Yamaguchi, M. Okamoto, and K. Hirano. Oscillations of the trapped flux in the early phase of a field-reversed θ -pinch. *Journal of the Physical Society of Japan*, 52:1215, 1983.
- ⁵L. C. Steinhauer. Plasma heating in field-reversed θ -pinches. *Physics of Fluids*, 26:254, 1983.
- ⁶M. I. Kutuzov, V. N. Semenov, and V. G. Strizhov. Trapping of magnetic flux during the formation of a compact toroid. *Sov. J. Plasma Physics*, 7:520, 1981.
- ⁷G. E. Vekshtein. Loss of magnetic flux during the formation of a FRC. *Sov. Phys. Dokl.*, 28:569, 1983.
- ⁸R. D. Milroy, J. T. Slough, and A. L. Hoffman. Plasma wall sheath contributions to flux retention during the formation of FRC's. *Physics of Fluids*, 27:1545, 1984.
- ⁹L. C. Steinhauer. Magnetic flux trapping during field-reversal in the formation of a FRC. *Physics of Fluids*, 28:3333, 1985.

- ¹⁰M. Tuszewski. Axial dynamics in field-reversed θ -pinches. In *7th Compact Torus Symposium*, Los Alamos National Laboratory, Los Alamos, NM, 1985. To be published in proceedings of that meeting.
- ¹¹W. T. Armstrong. FRC formation studies with z-discharge ionization on FRX-C. In *7th Compact Torus Symposium*, Los Alamos National Laboratory, Los Alamos, NM, 1985. To be published in proceedings of that meeting.
- ¹²M. Tuszewski, R. E. Chrien, and E. J. Yavornik. The FRX-C large source modification. In *7th Compact Torus Symposium*, Los Alamos National Laboratory, Los Alamos, NM, 1985. To be published in proceedings of that meeting.
- ¹³R. E. Chrien, M. Tuszewski, and E. J. Yavornik. The FRX-C large source modification. In *Proceedings of the 7th US-Japan Workshop on Compact Toroid Research*, page 33, Spectra Technology Inc., Bellevue, Washington, 1986.
- ¹⁴T. S. Green and A. A. Newton. Diffusion of antiparallel bias B-field during the initial stages of a θ -pinch. *Physics of Fluids*, 9:1386, 1966.
- ¹⁵W. T. Armstrong, J. C. Cochrane, R. J. Commisso, J. Lipson, and M. Tuszewski. θ -pinch ionization for FRC formation. *Applied Physics Letters*, 38:680, 1981.
- ¹⁶R. D. Milroy and J. U. Brackbill. Numerical studies of a FRC plasma. *Physics of Fluids*, 25:775, 1982.
- ¹⁷R. L. Spencer, M. Tuszewski, and R. K. Linford. Adiabatic compression of elongated FRC's. *Physics of Fluids*, 26:1564, 1983.
- ¹⁸M. Tuszewski. Experimental study of the equilibrium of FRC's. *Plasma Phys. and Contro. Fusion*, 26:991, 1984.
- ¹⁹R. L. Spencer and M. Tuszewski. Experimental and computational equilibria of FRC's. *Physics of Fluids*, 28:1810, 1985.

- ²⁰R. B. Webster and J. L. Schwarzmeier. Another FRC equilibrium code. In *Proceedings 1986 Sherwood Theory Conf.*, Courant Inst., New York, 1986. Paper 2C-12.
- ²¹W. T. Armstrong, R. K. Linford, J. Lipson, D. A. Platts, and E. G. Sherwood. Field-reversed experiments on compact toroids. *Physics of Fluids*, 24:2068, 1981.
- ²²J. T. Slough, A. L. Hoffman, R. D. Milroy, D. G. Harding, and L. C. Steinhauer. Flux and particle lifetimes measurements in FRC's. *Nuclear Fusion*, 24:1537, 1984.

FIGURES

FIG. 1. Schematic diagram of FRX-C/LSM showing sample vacuum magnetic flux surfaces and $B_z(z)$ -field on axis.

FRX-C/LSM Preionization

FIG. 2. Typical magnetic and interferometer data for a preionization (PI) discharge at low bias fields.

FRX-C/LSM Preionization

FIG. 3. Typical data for a PI discharge at intermediate bias fields.

+FRXC shot 6530 25-Feb-86 1340 mode 0 type 0 10241
 Bank-kV MB 49.8 CB 75.6 BB 3.4 PI 44.1 CU 0.0
 P-m torr TP10.23 PP\$2504
 Time-us
 ndl us b

FIG. 5. Time evolution of the radial integral density profile for a PI discharge with low bias field, $B_b \approx 0.75$ kG.

+FRXC shot 6681 25-Mar-86 1601 mode 0 type 0 10240
 Bank-kv MB 49.7 CB 75.1 BB 3.3 PI 43.9 CU 0.0
 P-mtrr TP10.07 PP\$2518
 Time-us
 ndl 150

FIG. 6. Time evolution of the axial integral density profile for a PI discharge with low bias, $B_b \simeq 0.75$ kG.

+FRXC shot 6538 25-Feb-86 1558 mode 0 type 0 10241
 Bank-KV MB 49.7 CB 75.4 BB 5.3 PI 44.5 CU 0.0
 P-motorr TP10.13 PP\$2504
 Time-us
 ndl 150

FIG. 7. Time evolution of the radial integral density profile for a PI discharge with intermediate bias, $B_b \approx 1.15$ kG.

+FRXC shot 6687 26-Mar-86 1013 mode 0 type 0 10240
 Bank-KV MB 49.7 CB 74.9 BB 5.5 PI 44.2 CU 0.0
 P-torr TP10.20 PPS2486
 Time-us
 ndl us z

FIG. 8. Time evolution of the axial integral density profile for a PI discharge with intermediate bias, $B_b \approx 1.15$ kG.

velocity field:

flux contours:

FIG.9a. The results of a numerical simulation of the preionization plasma in LSM using the Milroy-Brackbill code. The velocity vectors and the magnetic flux contours for $t = 3.2, 4.2, 6.2, 8.2, 10.2, 12.2$, and $14.2 \mu\text{s}$.

velocity field:

flux contours:

FIG. 9a. (cont)

FIG 9b. The results of a numerical simulation of the preionization plasma in LSM using the Milroy-Brackbill code. Axial profiles of the line density and line integrated density (f_{ndl}) for $t = 3.2, 4.2, 6.2, 8.2, 10.2, 12.2,$ and $14.2 \mu\text{s}$.

FIG. 9b. (cont)

FIG. 10. Typical magnetic and interferometer data for a PI and mainbank discharge at low bias fields with $\Delta T_{PI} = 12 \mu s$.

FIG. 11. Time evolution of the excluded flux radius profile during FRC formation at low bias, $B_b \simeq 0.75$ kG and $\Delta\tau_{PI} = 12$ μs .

FIG. 12. Time evolution of the axial integral density profile during FRC formation at low bias, $B_b \approx 0.75$ kG and $\Delta\tau_{PI} = 12 \mu\text{s}$.

FRXC shot 6468 6-Feb-86 1113 mode 0 type 0 10241
 Bank-KU RB 49.7 CB 75.4 BB 3.6 PI 46.5 CU 0.0
 P-mirror TP10.07 PP82801
 Time-us
 ndl vs b

FIG. 13. Time evolution of the radial integral density profile during FRC formation at low bias, $B_b \simeq 0.75$ kG and $\Delta\tau_{PI} = 12 \mu\text{s}$.

FIG. 14. Variation of "zero-crossing" field, $B_{zc} = \Phi_t(B_{ext} = 0)/\pi r_t^2$, with bias field for $\Delta\tau_{PI} = 5 \mu s$ (Δ), $12 \mu s$ ($\circ$), and $30 \mu s$ ($\times$).

FIG. 16. Time evolution of the excluded flux radius profile during FRC formation at $B_b = 1.15$ kG and $\Delta\tau_{PI} \approx 12$ μs .

FIG. 17. Time evolution of the axial integral density profile during FRC formation at $B_b = 1.15$ kG and $\Delta\tau_{PI} = 12 \mu\text{s}$.

FRXC shot 6508 21-Feb-86 1028 mode 0 type 0 10241
 Bank-LV MB 49.7 CB 75.2 BB 5.9 P1 47.4 CU 0.0
 P-motor TP10.25 PR2541
 Time-us
 ndl vs b

FIG. 18. Time evolution of the radial integral density profile during FRC formation at $B_b = 1.15$ kG and $\Delta\tau_{PI} = 12$ μ s.

FIG. 19. Ratio of FRC minimum lengths inferred from interferometry and excluded flux plotted against the observed zero-crossing B-field for $\Delta\tau_{PI} = 5 \mu s$ (Δ), $12 \mu s$ (o), and $30 \mu s$ ($\times$).

FIG. 20. The maximum excluded flux radius and minimum integral density lengths measured during FRC formation plotted against the zero-crossing field for $\Delta\tau_{PI} = 5 \mu s$ (Δ), $12 \mu s$ (o), and $30 \mu s$ (x).

FIG. 21. The variation of the minimum FRC elongation with zero crossing field for $\Delta\tau_{PI} = 5 \mu s$ (Δ), $12 \mu s$ (o), and $30 \mu s$ ($\times$).

FIG. 22. Variation with B_{zc} of the poloidal flux inferred from measurements at time $t = 20 \mu s$ using Eq. (1) for $\Delta\tau_{PI} = 5 \mu s$ (Δ), $12 \mu s$ ($\circ$), and $30 \mu s$ ($\times$).

FRXC shot 6534 wall=38.0 avn= 6
data fits

FIG. 23. (a) Radial profile of the integral density measured near the start of the equilibrium phase for a FRC formed at low bias $B_b = 0.75$ kG; (b) $n(r)$ profile inferred from Eqs. (2) and (3).

FIG. 24. (a) Radial profile of the integral density measured near the start of the equilibrium phase for a FRC formed at high bias, $B_b \approx 1.3$ kG; (b) $n(r)$ profile inferred from Eqs. (2) and (3).

FIG. 25. Time evolution of the axial integral density profile during the equilibrium phase of an FRC formed at low bias $B_b \simeq 0.75$ kG.

FRXC shot 6665 25-Mar-86 910 mode 0 type 0 10240
 Bank-ku MB 49.7 CB 75.4 BB 3.3 PI 44.2 CU 0.0
 P-materr TP10.07 PP82509
 Time-us

FIG. 26. Time evolution of the excluded flux radius profile during the equilibrium phase of an FRC formed at low bias, $B_b \simeq 0.75$ kG.

MIRROR EFFECTS ON $\langle \beta \rangle$ IN LSM: $x_s = 0.474$

FIG. 27. Changes in $\langle \beta \rangle$ with plasma length computed for (a) "racetrack" and (b) elliptical FRC separatrices. The length of the straight central section of the LSM θ -pinch coil is 140 cm.

FIG. 28. Typical $\Phi_p(t)$ data for four discharges inferred from external magnetic measurements and Eqs. (1), (4), and (5).

FIG. 29. Histograms illustrating the relative frequency of occurrence for the four flux decay modes.

FIG. 30. Variation of the FRC length as estimated using: a) the excluded flux radius, b) f_{ndl} , and c) the line density for a typical MHD simulation of FRC formation in LSM.

(a)

FLUX CONTOURS

(b)

DENSITY CONTOURS

FIG. 31. The magnetic flux contours and the electron density contour at $t = 16 \mu\text{s}$ for the same MHD simulation as in Fig. 30.