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TITLE: FORMATION AND CONFINEMENT OF FRCs IN FRX-C/LSM

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FORMATION AND CONFINEMENT OF FRCs IN FRX-C/LSM[1]

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1. Introduction

The Large Source Modification of FRX-C (FRX-C/LSM) consists of a 50% increase in radius without a commensurate increase in either the coil length or capacitor bank energy. Previous studies in FRX-C/LSM compared tearing and nontearing formation in a coil arrangement which included passive mirrors and auxiliary cusp coils[1]. The present studies use a straight coil (0.35 m radius, 2.0 m length) without passive mirrors; in this case, the cusp coils promote nontearing formation and provide mirror fields to inhibit axial drifting. This arrangement increases the length (from 1.3 to 2.0 m) and the length-to-diameter ratio (from 1.7 to 2.9) of the uniform field region. It also increases the implosion electric field from 28 to 32 kV/m. These changes tend to produce more elongated FRCs, but in all cases the axial equilibrium appears not to be influenced by the mirror fields. The FRCs are formed using a deuterium static fill varying from 2 to 10 mtorr, a bias field varying from 0.05 to 0.10 T, and preionization consisting of a zero-crossing ringing θ-pinch discharge aided by a 10 MHz RF generator.

2. Low-Density FRC Confinement Studies

The best confined FRCs in FRX-C/LSM are formed using fill pressures of 2–4 mtorr. Equilibrium parameters have the typical range $n \approx 0.5$–1.2×10^{21} m^{-3}, $(T_i + T_e)/2 \approx 170$–$400$ eV, $B \approx 0.35$–0.55 T, separatrix radius $r_s \approx 0.14$–0.18 m, trapped flux ≈ 3–5 mWb, s parameter 1.0–2.2, $\ell_s \approx 1.8$ m, and $\langle\beta\rangle \approx 0.9$. Confinement times for particles, flux, and energy of $\tau_N \approx 250$ μs, $\tau_\phi \approx 270$ μs, and $\tau_E \approx 100$ μs are obtained by fitting data from collections of similar discharges.

For 3-mtorr low-field ($B \approx 0.39$ T) conditions, the electron temperature at the field null was measured by Thomson scattering to be 140 ± 20 eV during the equilibrium phase. This temperature exceeds the values obtained at similar magnetic field in smaller FRCs[2] (80–100 eV) and also the prediction of an open field line thermal conduction model[3] (70–80 eV).

The particle confinement has been compared with a transport model[4] based on lower hybrid drift (LHD) resistivity. For 2–3 mtorr FRCs, τ_N exceeds the LHD prediction by a factor 1.5–2 (Fig. 1) while for 4 mtorr the measurements fall below the LHD prediction. The inferred[2] flux confinement has been compared with models based on classical perpendicular resistivity. For 2–3 mtorr FRC's, the prediction exceeds the measured τ_ϕ by a factor 10–20; for 4 mtorr the anomaly is 15–50. These anomaly factors are larger than the values 3–7 usually observed in smaller FRC's[5].

A zero dimensional power flow analysis[6] was performed for the 3 mtorr low field conditions. The major loss channel is particle convection (5/2 kT per particle), accounting for about 70% of the total losses. The remaining part of the energy loss appears in the electron channel and probably represent anomalous cross field thermal conduction. In comparison with the power flow analysis of smaller 5 mtorr FRC's in FRX-C[2] with similar collisionality, both the convection and conduction channels show an improvement in confinement by a factor 3.4. Of this improvement, one might ascribe a factor 1.9 to the increase in r_s^2/ρ_{io}, a factor 1.4 to the x_s scaling predicted by LHD theory, and the remaining factor 1.3 to other improvements for the FRX-C/LSM conditions.

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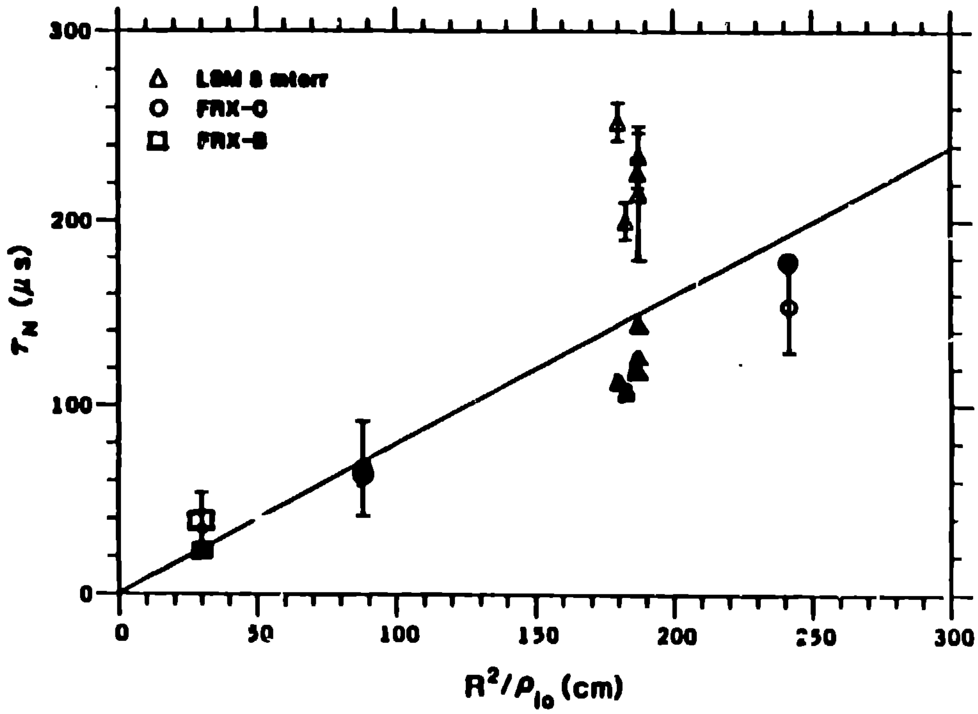

Figure 1: Scaling of particle confinement time τ_N with R^2/ρ_{io} (where $R = r_s/\sqrt{2}$) in the FRX-B (r_{coil} = 0.12 m), FRX-C (r_{coil} = 0.25 m), and FRX-C/LSM (r_{coil} = 0.35 m) experiments. Open symbols represent measured τ_N and solid symbols represent predictions of LHD transport theory. Each FRX-C/LSM data point represents a collection of 3 mtorr low-field discharges.

3. FRC Formation Studies

The three most important experimental parameters affecting FRC formation in FRX-C/LSM are the fill pressure, the strength of the bias field, and the timing of the ringing theta-pinch preionization. The effect of these parameters was observed by using an axial array of side-viewing interferometer chords to monitor axial contraction strength, an end-viewing visible (500–600 nm) framing camera with 0.2 μs exposure time to monitor azimuthal symmetry during the preionization and formation up to the axial contraction, and the usual excluded flux diagnostic to monitor τ_ϕ and τ_E during the equilibrium as a measure of the quality of formation. Recently, an end-viewing soft x-ray pinhole camera (10–20 nm) with 2 μs exposure time has been used (in collaboration with E. A. Crawford[7]) to monitor azimuthal symmetry of the $T_e \sim 20$–30 eV plasma after the radial implosion.

At preionization timings for which good confinement could be obtained, measurements of the axial variation of the line-integral density distribution indicate that the density profile is relatively uniform at the start of formation. Visible framing photographs show a current sheath which is fairly symmetric azimuthally for all conditions, exhibits radial oscillations, and appears to be leaning on the inner wall of the quartz vacuum chamber at the best formation times.

For low fill pressures, a transition from good to bad confinement occurs as the bias field is raised and an axial shock occurs during formation. This transition occurs for similar values of axial shock strength for 2–4 mtorr FRC's in FRX-C/LSM, and in 5 mtorr FRC's in FRX-C[8], when the (inverse) axial shock strength is measured by the transient minimum elongation ϵ_{min} of the $\int n\,dl$ profile normalized by the initial elongation. The onset of axial shocks is observed at lower bias field than in the smaller FRX-C experiments. This behavior is related to reduced radial and resistive heating during the radial implosion and compression because of the increased size in FRX-C/LSM[9].

The separatrix shape of the low fill pressure FRC's, as observed with the x-ray camera, tends to be azimuthally symmetric or exhibit low toroidal mode number, low amplitude asymmetries.

During the equilibrium, an on-axis intensity minimum is usually observed in the better FRCs (Fig. 2(a)) similar to the TRX visible continuum measurements described later in this paper. A wide variation in confinement is observed for FRCs which exhibit similar degrees of asymmetry. However, the confinement tends, on average, to correlate with the symmetry. The correlation is similar for asymmetries observed during formation or during the equilibrium.

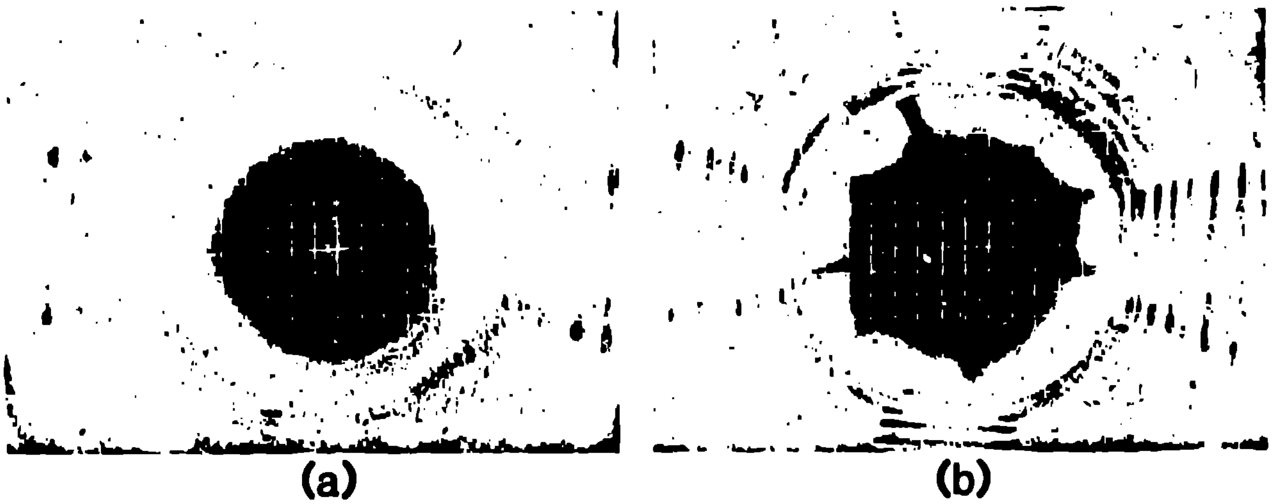

Figure 2: End-viewing x-ray photographs of the FRC separatrix shape for (a) optimum 3 mtorr conditions at $t = 41$ μs and (b) 5 mtorr conditions at $t = 6$ μs.

For fill pressures exceeding 4 mtorr, consistently good confinement could not be obtained. Between 4 and 5 mtorr, gross asymmetries begin to appear following the radial implosion. The asymmetries are characterized by large toroidal mode number and amplitude and suggest a fluting instability. At 5 mtorr sharp spikes are observed on the separatrix, especially at high bias (Fig. 2(b)); these features become less pronounced at higher fill pressure. The behavior of the axial contraction also changes at these fill pressures. FRCs formed at 5 mtorr always contract strongly ($\epsilon_{md} > 2$), regardless of bias field, and the confinement is always poor. In particular, very short transient elongations ($\epsilon_{md} < 1.5$) are observed at low bias field (≤ 0.05 T) under conditions for which only a weak to moderate axial contraction is expected based on the predictions of a formation model[9] which correctly predicts the onset of axial shocks in the 2–4 mtorr data. At 10 mtorr, ϵ_{md} varies greatly for a given bias field as a result of variations in the amount of bias flux remaining after the preionization. The variation of τ_ϕ with ϵ_{md} is similar to that of the 2–4 mtorr FRCs, except that consistently good confinement is not observed for weak axial contractions.

4. Discussion

FRC confinement and reproducibility has improved considerably in the present coil geometry in comparison with previous FRX-C/LSM results[1]. Since the largest hardware change was the increase in coil elongation, this improvement suggests the importance of forming FRCs with sufficient elongation and avoiding interaction of FRCs with mirror fields. The best FRCs in FRX-C/LSM have particle confinement up to twice the prediction of LHD transport theory. These FRCs are sufficient in all respects for heating to $T_e \sim 1$ keV in high power magnetic compression experiments during 1989–90. However the flux confinement in FRX-C/LSM shows larger resistivity anomalies than in smaller FRCs. The 4 mtorr data represent the beginning of a transition to irreproducible or generally poor formation observed at higher fill pressures. The degradation of particle confinement in conjunction with reduced flux confinement in the 4 mtorr case is consistent with the general pattern in FRC's that $\tau_N \lesssim \tau_\phi$.

Formation studies in FRX-C/LSM have identified two mechanisms for a transition from good to bad confinement. At low fill pressures, the onset of an axial shock as the bias field is increased correlates well with degradation in flux confinement, as previously observed in FRX-C. Axial shocks degrade confinement in FRX-C/LSM in spite of three improvements over formation in FRX-C: nontearing formation, higher viscosity, and optimum timing of the axial contraction at peak field. The axial contraction limitation is more severe in FRX-C/LSM because of reduced radial and resistive heating that accompanies the increase in radial dimension. At high fill pressure, gross fluting of the separatrix is observed prior to the peak of the axial contraction and axial shocks are unexpectedly difficult to avoid. These flute-like distortions are similar to those observed in hybrid simulations of expanding plasmas and which are attributed to deceleration-driven lower hybrid drift instabilities[10]. Further work is needed to understand these phenomena and to assess the relationship (if any) between fluting and axial shocks.

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