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TITLE: THEORETICAL AND EXPERIMENTAL STUDIES OF FIELD-REVERSED CONFIGURATIONS

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MASTER

Abstract

The FRX-C/T formation region has been enlarged in diameter by 50%, and quasi-steady cusp coils have been installed to compare tearing and non-tearing formation. FRCs with significantly larger poloidal flux ($\leq$ 8 mWb) and s ($\leq$ 4) have been formed. However, their flux confinement was degraded compared with earlier FRX-C results.

The n=2 rotational instability has been completely suppressed on translated FRCs in FRX-C/T. Nearly equal stabilization thresholds were observed for straight and helical quadrupole fields, in contrast with another experiment.

STUDIES OF TEARING AND NON-TEARING FORMATION IN LSM

A. Introduction

The FRX-C/T device[S1] has been modified by enlarging the diameter of the FRC formation region by 50%. This larger formation region (termed LSM for Large Source Modification) will be more suitable for future translation and adiabatic compression experiments; it has to date been used (without translation) to study the processes governing FRC formation. An important experimental objective is to achieve the maximum possible trapped poloidal flux ϕ_p in the larger source (corresponding to maximum s) in order to obtain optimum confinement and to look for the tilt instability. Improved FRC formation in small (0.2 → 0.3 m) diameter devices has been reported when field line tearing and reconnection is avoided[S2,S3]. Installation of quasi-steady cusp coils on LSM has permitted comparisons of tearing and non-tearing formation in a larger device which are reported here. It was found that larger-radius FRCs (up to 0.21 m), with increased values of the inferred ϕ_p ($\leq$ 8 mWb) and s ($\leq$ 4), could be formed in LSM. However, their flux confinement, in both tearing and non-tearing operation, was degraded compared with that obtained in earlier FRX-C experiments[S4,S5].

B. Description of Experiment

The measurements were obtained with the formation geometry and magnetic characteristics listed in Table I. The plasma was created in an initial 10 mtorr static fill of deuterium gas (except for 2 mtorr results in section E.). The preionization method consisted of an initial seed ionization produced by a 10 MHz generator coupled to antennas at each end of the coil, followed by full ionization produced by a 175 kHz ringing Θ-pinch discharge. The capacitor bank energies and voltages were unchanged from earlier FRX-C operation. Thus the azimuthal electric field at the quartz tube during field-reversal was decreased from 37 kV/m in FRX-C to 28 kV/m in LSM. Another significant change was the decrease in Θ-pinch coil elongation (length between mirror peaks to central diameter ratio) from 3.6 to 2.1, which tended to reduce the FRC elongation and increase the influence of the mirror fields on the FRC equilibrium. The passive mirror ratio of 1.20 was sufficient to prevent FRCs from drifting axially out of the coil following formation (a mirror ratio of 1.11 was found to be inadequate).

TABLE I - Characteristics of LSM

Formation Geometry	
Θ-Pinch Coil Length (overall)	2.01 m
Coil Central Diameter (1.4 m long)	0.76 m
Passive Mirror Diam. (0.3 m each end)	0.66 m
Magnetic Mirror Ratio (on axis)	1.20
Quartz Chamber I.D.	0.60 m
Magnetic Fields	
Main Field Swing (vacuum)	0.6 T
Main Field Rise Time (τ/4)	6.7 μs
Main Field Decay Time (L/R)	500 μs
Θ-Preionization Field Amplitude	0.08 T
Bias Field (maximum)	0.13 T
Cusp Field (maximum on axis)	0.30 T
Cusp Field Rise Time (τ/4)	4 ms

C. Tearing versus Non-Tearing Formation

After performing initial tests of tearing formation, cusp coils were installed at each end of the Θ-pinch coil to permit direct comparison of tearing and non-tearing formation. The two formation techniques are illustrated by the 2-D MHD simulations[$6] shown in Figure %1. The simulations indicated that cusp field strength $B_{cusp} \geq 0.05 \rightarrow 0.10$ T was needed to avoid tearing and ejection of part of the plasma at each end. This transition was qualitatively confirmed by a large reduction in visible light observed at the end during non-tearing formation.

Cusp fields were found to enhance flux trapping. This enhancement was particularly noticeable at weak bias field B_b (B_b < 0.08 T) for which the "zero-crossing" flux, $\phi_{zc} = \phi(B_v = 0)$, was increased by 1.3 → 2.5 times that obtained with $B_{cusp} = 0$.

The use of cusp coils was observed to improve the symmetry (about the axial midplane) of FRC formation. One way to quantify the improved symmetry was to observe the maximum axial speed of the FRC's separatrix volume. The corresponding axial kinetic energy decreased monotonically from 28 J to 8 J as B_{cusp} was increased from 0 to 0.2 → 0.3 T. The observed improvement in formation symmetry was consistent with the transition from tearing to non-tearing formation as predicted by the simulations.

The axial contraction tended to be stronger for non-tearing formation. The strength of the axial contraction was estimated using the minimum elongation ε_{min} defined as the ratio of the (FWHM) length of the FRC measured using an axial array of interferometers to the maximum diameter inferred from the separatrix radius profile. The ε_{min} values were 1.2 → 1.8 without tearing and 2.0 → 3.5 with tearing (for B_b = 0.07 → 0.09 T). The axial contraction also took place earlier without tearing.

For the formation conditions which optimized confinement, larger ϕ_p values could be retained in the equilibrium FRC with non-tearing formation. An example of the parameters of one of the best FRCs formed using non-tearing formation is shown in Figure %2. The largest average ϕ_p values (5.8±0.6 mWb, where the error estimates denote standard deviations) were obtained for B_{cusp} = 0.2 → 0.3 T and B_b = 0.08 → 0.09 T ("cusp on" condition).

When $B_{cusp} = 0$ ("cusp off" condition), ϕ_p was lower (2.3±0.5 mWb for B_b = 0.065 → 0.075 T). However, larger ϕ_p with tearing formation (3.5±0.6 mWb) could be obtained under similar conditions before the cusp coils were installed ("no cusp" condition). Thus it appeared that the currents induced in the cusp hardware were detrimental to the tearing formation process.

Corresponding to the larger ϕ_p, larger values of s (up to 4) were also attained with non-tearing formation. In the "cusp on" condition, s values of 2.7±0.4 were observed at 30 μs after field-reversal. In the "cusp off" condition, the s values were 1.9±0.4. Both ϕ_p and s were inferred from external measurements assuming a typical diffuse profile[S5] that matched FRX-C data. Further work is needed to determine the most appropriate profile for LSM conditions.

D. FRC Confinement

The confinement times of flux (τ_ϕ), particles (τ_N), and energy (τ_E) were determined over an interval from the start of the axial equilibrium (t = 30 μs) to the appearance of the n=2 mode (t = 70±10 μs). When no n=2 oscillations occurred, the time the separatrix radius began to decay more rapidly was chosen to end the interval.

The flux confinement of FRCs produced in LSM was, on average, degraded compared with that observed in earlier FRX-C experiments. Similar average τ_ϕ values were observed for "cusp on" (τ_ϕ = 58±40 μs) and "cusp off" (τ_ϕ = 50±22 μs) conditions. Somewhat better average flux confinement was observed during tearing formation in the "no cusp" condition (τ_ϕ = 110±45 μs). The maximum τ_ϕ was about 200 μs. The absence of T_e measurements prevented detailed comparisons with classical flux confinement predictions. However, the resistivity anomaly with respect to the classical resistivity of a 100 eV plasma (assuming a rigid rotor FRC profile) was in the range 15 → 30. This was significantly larger than the resistivity anomaly (3 → 7) measured in FRX-C[S4,S5].

The particle confinement in LSM improved with τ_ϕ ($\tau_N \approx 1.2\tau_\phi$). For those FRCs with greater than average τ_ϕ values, τ_N was, on average, a factor of two smaller than the predictions of a transport theory based on lower hybrid drift turbulence[S7]. The global energy confinement times[S8] scaled with τ_N ($\tau_E \approx \tau_N/2$) in a manner consistent with an energy balance dominated by particle convection.

E. Low Fill Pressure Operation

A data run at 2 mtorr was conducted in which hotter ($T_e + T_i \lesssim 0.8$ keV) and less dense ($\bar{n} \approx 5\times10^{20}$ m^{-3}) FRCs were formed. The best confinement, τ_ϕ = (75±35) μs, could only be achieved with non-tearing formation (B_{cusp} = 0.25 T) and weak bias ($B_b \approx 0.04$ T). Tearing formation at 2 mtorr resulted in poor confinement with τ_ϕ < 35 μs for any B_b. For non-tearing formation strong axial contractions were observed and the equilibrium values of ϕ_p (= 2.6±0.3 mWb) and s (≈ 1.0) were smaller than those inferred at 10 mtorr because of the lower B_b and higher T_i.

F. Discussion

LSM experiments (and formation simulations) have shown several advantages in the use of auxiliary quasi-steady cusp coils for FRC formation. First, cusp fields in sufficient strength permit FRC formation without field line tearing and reconnection driven by mirror fields. This eliminates the necessity for those mirror fields during formation. Second, non-tearing formation is more symmetric, resulting in less axial speed. Third, FRCs with larger ϕ_p and s can be formed in the non-tearing mode. Fourth, FRC formation was possible at low (2 mtorr) fill pressure with non-tearing formation. These advantages were attained in LSM without the complexity of rapidly pulsed auxiliary coils and precise timing necessary for "balloon"[S2] or "programmed"[S3] formation modes.

Flux confinement was degraded in LSM compared with earlier tearing formation results in FRX-C, independent of the formation mode used. The degraded confinement is not presently understood. Some possible explanations are poor formation, low T_e, FRC elongations that are too small (either transiently or in equilibrium), interaction with mirror fields, and instability to the tilt mode. The possibility of low T_e will be tested by Thomson scattering measurements. Elongation and mirror effects can be ameliorated by a change in coil geometry (e. g. a 0.70 m diam. coil without passive mirrors) or by translation experiments using the FRX-C/T translation region. We have attempted to identify tilt instability by searching for m=1, n=1 magnetic perturbations (B_θ) outside the quartz vacuum chamber. No evidence for the tilt mode has been detected by this method (but it is not clear whether the probe sensitivities (10^{-3} T) are adequate to detect the largely internal mode predicted by linear theory). It is also worth noting that formation at low bias field or fill pressure resulted in FRCs with the same range of s as in FRX-C and yet continued to show lower τ_ϕ values. This indicates that formation or equilibrium problems are more likely than tilt instability to be responsible for the degraded flux confinement.

HELICAL AND STRAIGHT QUADRUPOLE STABILIZATON EXPERIMENTS

The n=2 rotational instability has been completely suppressed on translated FRCs in the FRX-C/T device[S1] by the application of either helical or straight quadrupole fields, as discussed in detail elsewhere.[S9] The most extensive data base was obtained for the low-compression, 5-mtorr D_2-puff mode in which translated FRC parameters were: $\bar{n} = 8 \times 10^{20}$ m^{-3}, $T_e + T_i \approx 0.45$ keV, external axial B-field $B_v \approx 0.4$ T, $x_s = 0.6$. Well-defined quadrupole field thresholds were found above which complete stabilization was observed. There was indirect evidence, however, that the rotation was not stopped. Threshold magnitudes approximately equal to 7% and 9% of the external confinement field were found with the straight and helical fields, respectively. The observation of comparable helical and straight quadrupole field thresholds was different from that observed on the NUCTE-II device[S10] in which substantially larger straight fields were needed to suppress the n=2 mode (Another helical and straight stabilization comparison is reported in these proceeding[$11]). One noteworthy difference between the two experimental configurations was the three-times-larger pitch of the FRX-C/T helical coil.

The straight quadrupole threshold on FRX-C/T was about four times smaller than theoretical predictions[$12] based on the MHD approximation for a circular plasma separatrix with mode coupling ignored. In order to include both the modification of the equilibrium due to the quadrupole field and ion kinetic effects, computer simulations have been performed using a 2-1/2-D nonlinear, time-dependent, quasineutral hybrid simulation code[$13] for the straight quadrupole case. The simulations were initialized with an axisymmetric rigid-rotor distribution in which the density was truncated beyond the separatrix. The simulations predicted a well-defined stability threshold of approximately twice that observed on FRX-C/T. This discrepancy between theory and experiment is believed to be due to differences in equilibria.

With quadrupoles stable FRC lifetimes in the translation region up to 300 μsec were observed. A 0-D confinement analysis[$14] resulted in the following conclusions: (1) the energy confinement time, $\tau_E \lesssim 100$ μs, remained unchanged with quadrupole strength up to either threshold although it was degraded for larger straight fields; (2) the particle confinement time τ_N increased, on average, by 50% (to over 200 μs) with the helical fields; (3) changes in τ_N caused by the straight fields were not evident; (4) the poloidal flux confinement time, $\tau_\phi \lesssim 260$ μs decreased by about 30% when the threshold fields were applied.

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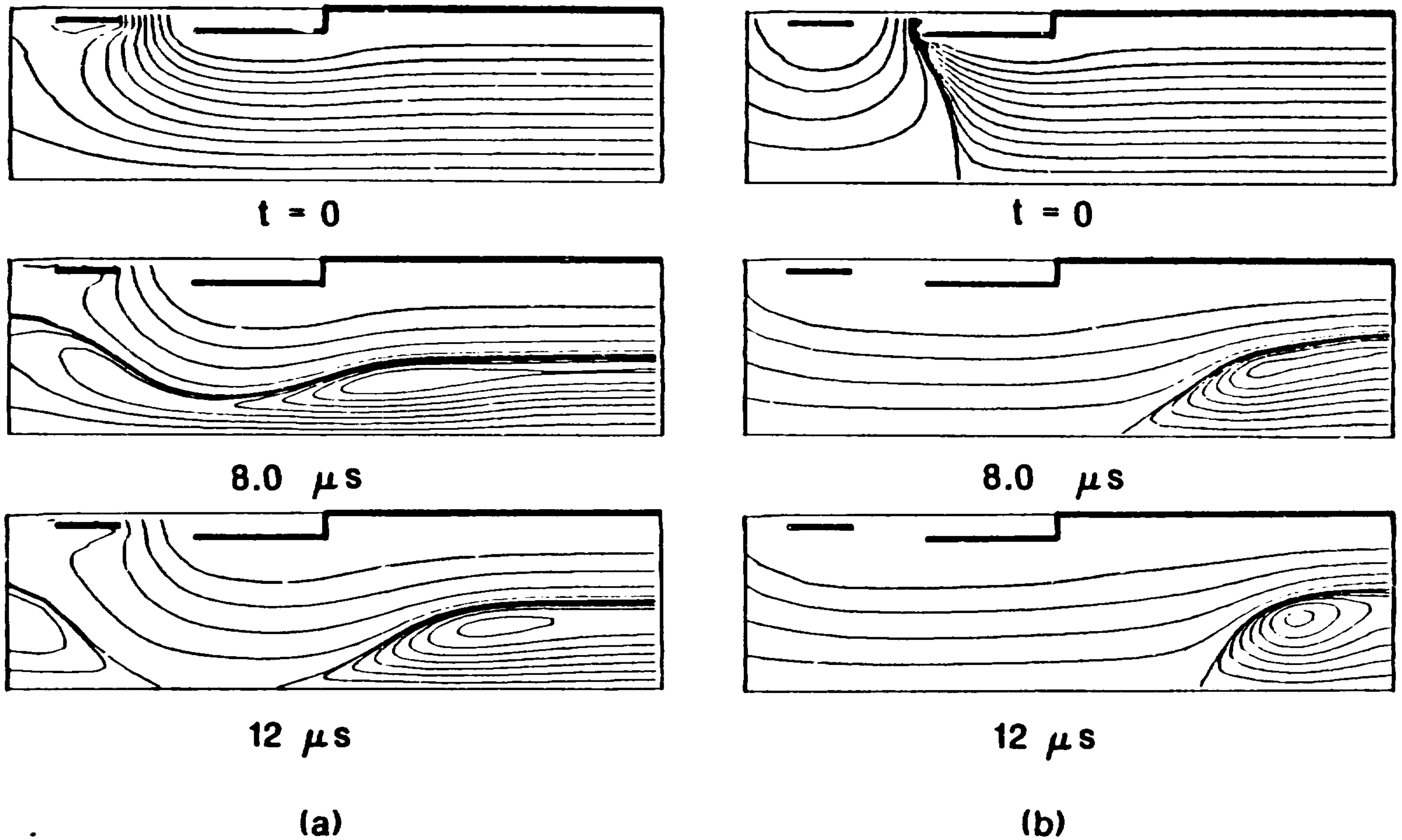
FIGURES

Fig. %1. Configuration of LSM formation region showing simulations of (a) tearing and (b) non-tearing formation. In tearing formation, the closed field lines tear and reconnect under the passive mirrors after the main field has risen. In non-tearing formation, cusp coil fields drive in axially the pre-formed FRC separatrix shortly after field-reversal thereby preventing tearing.

Fig. %2. Time evolution of the external magnetic field, separatrix radius, average density, and average temperature ($(T_i + T_e)/2$) for one of the best FRCs formed without tearing. The equilibrium ($t = 30$ μs) was characterized by $x_s = 0.50$, $\phi_p = 6.7$ mWb, and $s = 3.0$. The confinement times ($t = 30 \rightarrow 100$ μs) were $\tau_\phi = 130$ μs. $\tau_N = 250$ μs, and $\tau_E = 85$ μs.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(a)
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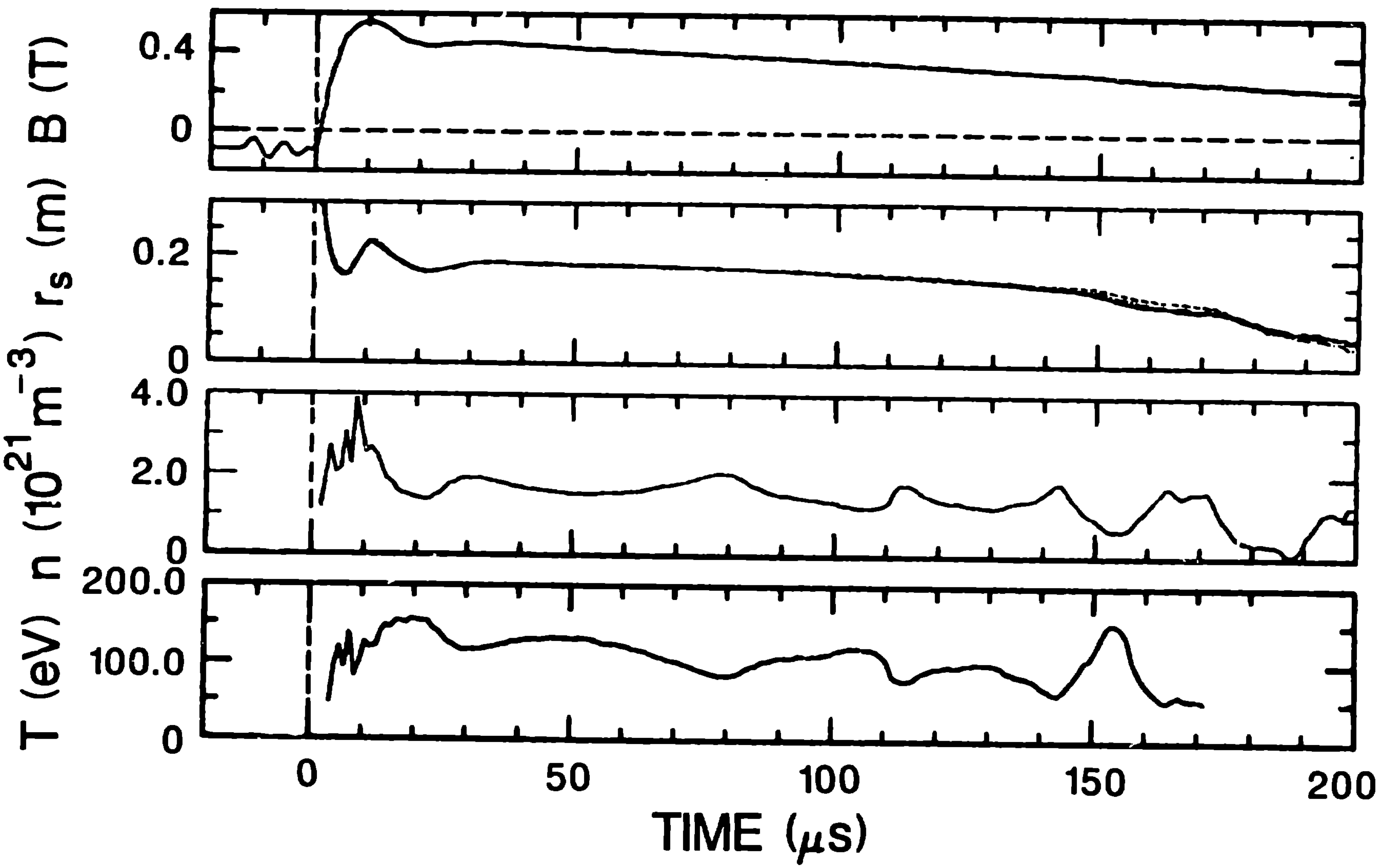
(b)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