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TITLE FIELD-REVERSED CONFIGURATION (FRC) EXPERIMENTS

AUTHOR(S) R.E. Siemon, R.E. Chrien, W.N. Hugrass, S. Okada, D.J. Rej,
D.P. Taggart, M. Tuazewski, R.B. Webster, B.L. Wright,
J.T. Slough, E.A. Crawford, A.L. Hoffman, R.D. Milroy,
G.C. Vlases, R.D. Brooks, B. Kronast, Z.A. Pietrzyk, R. Raman,
R. Smith

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R. E. SIEMON, R. E. CHRIEN, V. N. HUGRASS*, S. OKADA**, D. J. REJ,

D. P. TAGGART, M. TUSZEWSKI, R. B. WEBSTER, B. L. WRIGHT

Los Alamos National Laboratory

Los Alamos, New Mexico, United States of America

J. T. SLOUGH, E. A. CRAWFORD, A. L. HOFFMAN, R. D. MILROY

Spectra Technology, Inc.

Bellevue, Washington, United States of America

G. C. VLASES, R. D. BROOKS, B. KRONAST***

Z. A. PIETRZYK, R. RAMAN, R. SMITH

University of Washington

Seattle, Washington, United States of America

Work supported by the United States Department of Energy

*Present Address: New England University, Armidale, Australia

**Permanent Address: Osaka University, Osaka, Japan

***Permanent Address: Ruhr Universität, Bochum, F. R. G.

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FIELD-REVERSED CONFIGURATION (FRC) EXPERIMENTS

FRCs with equilibrium separatrix radii up to 0.18 m have been formed and studied in FRX-C/LSM. For best formation conditions at low fill pressure, the particle confinement exceeds the predictions of LHD transport calculations by up to a factor of two; however, the inferred flux confinement is more anomalous than in smaller FRCs. Higher bias field produces axial shocks and degradation in confinement, while higher fill pressure results in gross fluting during formation. FRCs have been formed in TRX with s from 2 to 6. These relatively collisional FRCs exhibit flux lifetimes of 10 → 20 kinetic growth times for the internal tilt mode. The coaxial slow source has produced annular FRCs in a coaxial coil geometry on slow time scales using low voltages.

1. CONFINEMENT AND FORMATION IN THE FRX-C/LSM EXPERIMENT

1.1 Description of Experiment

Previous studies in 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 33 kV/m. These changes tend to produce more elongated FRCs, but in all cases the axial equilibrium of the FRCs 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.

1.2 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 $n = 0.5 \rightarrow 1.2 \times 10^{21} \text{ m}^{-3}$, $(T_i + T_e)/2 = 170 \rightarrow 400 \text{ eV}$, $B = 0.35 \rightarrow 0.55 \text{ T}$, separatrix radius $r_s = 0.14 \rightarrow 0.18 \text{ m}$, trapped flux = 3 → 5 mWb, s parameter = 1.0 → 2.2, $l_s = 1.8 \text{ m}$, and $\langle \beta \rangle = 0.9$. Confinement times for particles, flux, and energy of $\tau_N \leq 250 \mu\text{s}$, $\tau_\phi \leq 270 \mu\text{s}$, and $\tau_E \leq 100 \mu\text{s}$ are obtained by fitting data from collections of similar discharges.

For 3-mtorr low-field ($B = 0.39 \text{ T}$) conditions, the electron temperature at the field null was measured by Thomson scattering to be $140 \pm 20 \text{ eV}$ 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 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 FRCs, 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 FRCs[5].

A zero-dimensional power flow analysis[6] was performed for the 3 mtorr low-field conditions (Table I). 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 FRCs 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_{i0} , a factor 1.4 to the x_s scaling predicted by LHD theory, and the remaining factor 1.3 to other improvements for the LSM conditions.

1.3 FRC Formation Studies

The three most important experimental parameters affecting FRC formation in 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 μ s 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 with 2 μ s exposure time has been used (in collaboration with E. A. Crawford[7]) to monitor azimuthal symmetry of the $T_e > 20 \rightarrow 30$ 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. The correlation of the axial shock, as measured by a normalized minimum elongation parameter at peak axial contraction, with degradation in flux confinement is illustrated in Fig. 1, which also includes data from earlier axial contraction studies in FRX C[8]. 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 FRCs, 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, these asymmetries tend, on average, to correlate with degradation in confinement. The correlation is similar for asymmetries observed during formation or during the equilibrium.

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 (transient minimum elongation $\epsilon_{md} < 2$), 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.

1.4 Discussion

FRC confinement and reproducibility has improved considerably in the present coil geometry in comparison with previous 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 LSM have particle confinement up to twice the prediction of LHD transport theory. These FRCs are sufficient in all respects for heating to $T_1 \geq 1$ keV in high-power magnetic compression experiments during 1989-90. However the flux confinement in 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 in particle confinement in conjunction with reduced flux confinement in the 4 mtorr case is consistent with the general pattern in FRCs that $\tau_N \leq \tau_{\phi}$.

Formation studies in 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 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. Further work is needed to understand these phenomena and to assess the relationship (if any) between fluting and axial shocks.

2. EXPERIMENTAL STUDY OF FRCs AT LARGE s

FRCs have been predicted in numerous calculations to be unstable to the internal tilt mode[10] (ITM); yet FRCs have been found experimentally to persist for many MHD growth times[11] ($\tau_{\text{MHD}} \approx \text{length}/2v_A$). Ion kinetic effects have been calculated to considerably reduce the growth time when the effective number of internal ion gyroradii, represented by the parameter s , is small[1]. For all previously reported FRC experiments, s was less than or equal to 2, and the observed configuration time, which was governed by the flux decay rate, was never more than several kinetically adjusted growth times. It was possible, by operating the TRX experiment[12] at Spectra Technologies, Inc. well beyond its normal parameter space, to form FRCs at much higher values of s . This operation included use of high bias fields, high fill pressures, hydrogen rather than deuterium, and low final fields. Normally formation was impossible under these conditions due to severe implosion dynamics, but new improved operation techniques, such as high order barrier fields to symmetrize the implosion and reduce impurities, allowed high flux, cold FRCs to be formed in a small radius device. All of the above factors tend to increase s .

The cold ($T_i \approx 100$ eV), high flux ($\phi_p = 2-4$ mWb) FRCs formed under the above conditions experienced extreme axial dynamics, and did not exhibit the extremely favorable lifetime scaling with s noted with hotter, more gently formed FRCs[11] but they appeared to be grossly stable. The configuration lifetimes of about 100 μsec were similar to those of the lower s FRCs, and the flux lifetimes ranged from 40 to 110 μsec , with no clear dependence on s . The lack of continued lifetime improvement with increasing s could reflect either the increase of collisional resistivity at the lower temperature, or an increase in MHD activity.

It is significant that these cold, MHD-like FRCs survive as long as they do, since the internal tilt mode is predicted to be such a virulent instability. The measured flux lifetime τ_ϕ , normalized to the calculated tilt growth time, adjusted for kinetic effects, τ_{tilt} [11], is plotted on Fig. 3(a) versus s . FRCs are observed that survive for over ten predicted growth times, even when kinetic corrections are made to the calculated internal tilt growth rate.

The internal tilt mode is difficult to diagnose, especially during its early phases, since internal magnetic probes cannot be used. A non-perturbative diagnostic involves the use of end-on visible continuum radiation, which has been found to be more sensitive than end-on interferometry. Post processing of numerical equilibrium calculations shows that an annular profile is characteristic of a well formed FRC, and we have made use of this fact in previous evaluations of successful formation[11]. Experimentally (and numerically), this annular profile becomes more pronounced as s increases, eventually reaching a profile such as shown on Fig. 3(b). A 3-D numerical code was used to follow the development of the internal tilt of an MHD plasma [13], and post processing of those calculations shows the annular profile to disappear with the development of the tilt. Once annular profiles were observed experimentally, they were not observed to disappear, and the FRCs were not observed to be suddenly destroyed.

Previously, with less optimal formation techniques, FRCs could only be formed on TRX with s values up to 2. With the new formation improvements, annular appearing FRCs could be formed on TRX with s values up to about 4. The lack of successful formation at higher values of s could be attributed to either excessive dynamics (formation problem), or an exceedingly rapid tilt rate, perhaps aided by initial asymmetries. In the recent experiments, plasmas with inferred s values beyond 5 could be formed that had reasonable lifetimes (many axial flow times). However, these plasmas had a flat end-on radial intensity profile, and could not be called 'well-formed' FRCs. (Normalized decay rates are also shown for these plasmas on Fig. 3(a))

The present experimental results at high s indicate that the observed FRC stability may not be explained solely on the basis of ion kinetic effects. Numerical and analytic work is proceeding on other stabilizing mechanisms, such as plasma rotation or separatrix shaping. The final work must await the completion of a large s experiment, which will be capable of forming both high s and hot plasmas in a large radius device.

3. SLOW FORMATION OF ANNULAR FRCs IN THE COAXIAL SLOW SOURCE

The CSS experiment at the University of Washington was designed to create "annular FRCs" (AFRCs) on a diffusive time scale and at voltages of 1/10 to 1/50 of those used in conventional FRC generators. It produces closed-line poloidal-field-only plasma in the annulus between concentric θ coils 1-m long, with diameters of 0.12 and 0.42 m. The CSS was first operated with an effective risetime of 26 μ s [14], while the loop voltages remained ≤ 2 kV, and the preionization system and diagnostics were upgraded. With this new system, configuration lifetimes at fill pressures of 20 mtorr increased from 40 to 80 μ s. Since the Alfvén speeds in the plasmas which are produced have remained about the same, this indicates that plasma termination does not result from MHD instability. The CSS produces AFRCs over a range of pressure from < 4 to ≥ 80 mtorr, with typical trapped flux values of 6-10 mWb. Figure 4

shows traces from B_z probes at the midplane near the inner and outer coils for a range of filling pressures and constant voltages. It can be seen that following the initiation of field reversal there is a pressure-dependent dynamic phase, during which the waveforms show effects of both radial and axial motion. This is followed by a quasi-steady period with edge fields of 0.15 to 0.20 T. Plasma termination begins about the time of crowbar-induced wall contact, and its suddenness appears related to the thermal diffusivity.

In contrast to conventional FRCs, the separatrix in the CSS is not associated with a given flux surface, but moves from one to another as flux is supplied from the inner coil, creating nested near-vacuum flux surfaces surrounding the plasma. The inner flux surfaces contract toward the null, while the x-points move toward the coils ends and remain there. At 20 mtorr, Thomson scattering shows very high density ($> 10^{22} \text{m}^{-3}$) and low electron temperature ($= 7 \text{ eV}$) near the null at the time of peak field, $\approx 25 \text{ } \mu\text{s}$. This indicates very strong axial and radial compression of the inner, plasma-carrying flux surfaces. For weak curvature, B_z^2 is proportional to the plasma pressure (at the reversal layer). The temperature is probably clamped by the carbon radiation barrier, as less than .2% C could be needed to balance the Ohmic input power for these conditions. The plasma subsequently re-expands to about $n_e = 1.5 \times 10^{21} \text{m}^{-3}$, and heats to $T_e = 20 \text{ eV}$, where it may be limited by an oxygen radiation barrier. The postulate $T_i = T_e$ is consistent with both the calculated electron-ion equilibration rate and the external field.

The resistivity inferred from a simple analytical model of the flux balance is about $1.5 \times 10^{-4} \text{ } \Omega\text{-m}$, which is roughly 4 times classical for $Z=1$. Later in a given discharge the transport appears to improve. From Fig. 4 it is clear that the resistivity, which is reflected in the value of B achieved at the plasma edge, is somewhat lower at high fill pressures than at low, in direct contrast to classical predictions, for which $\eta \sim T^{-3/2} p_0^{3/2}$. The observed behavior scales more nearly as Bohm diffusion, or also according to a model by Krall based on high β low frequency instability theory[15]. This scaling tends to be confirmed by numerical modelling using a two dimensional, one temperature formulation with various transport models[16].

In conclusion, the CSS has satisfied its technological goals of producing FRCs at very low voltages and on slow time scales. Relatively low power input to the plasma leads to strong axial contraction, which in turn leads to severe radiation losses and holds the temperature down. The observed resistivity is several times classical for the 20 mtorr cases.

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Table I. Zero-Dimensional Power Flow Analysis for 3 mtorr FRCs

	E_p	\dot{E}_p	P_{cp}	P_Ω	P_{ei}	L_c	L_{nc}
Ions	6.1	-57	11	3	-27	44	0
Electrons	2.7	-12	5	2	27	20	27

E_p = thermal energy, P_{cp} = compression power, P_Ω = ohmic power, P_{ei} = equilibration power, L_c = convection losses, L_{nc} = losses other than particle convection (energies in kJ, powers in MW).

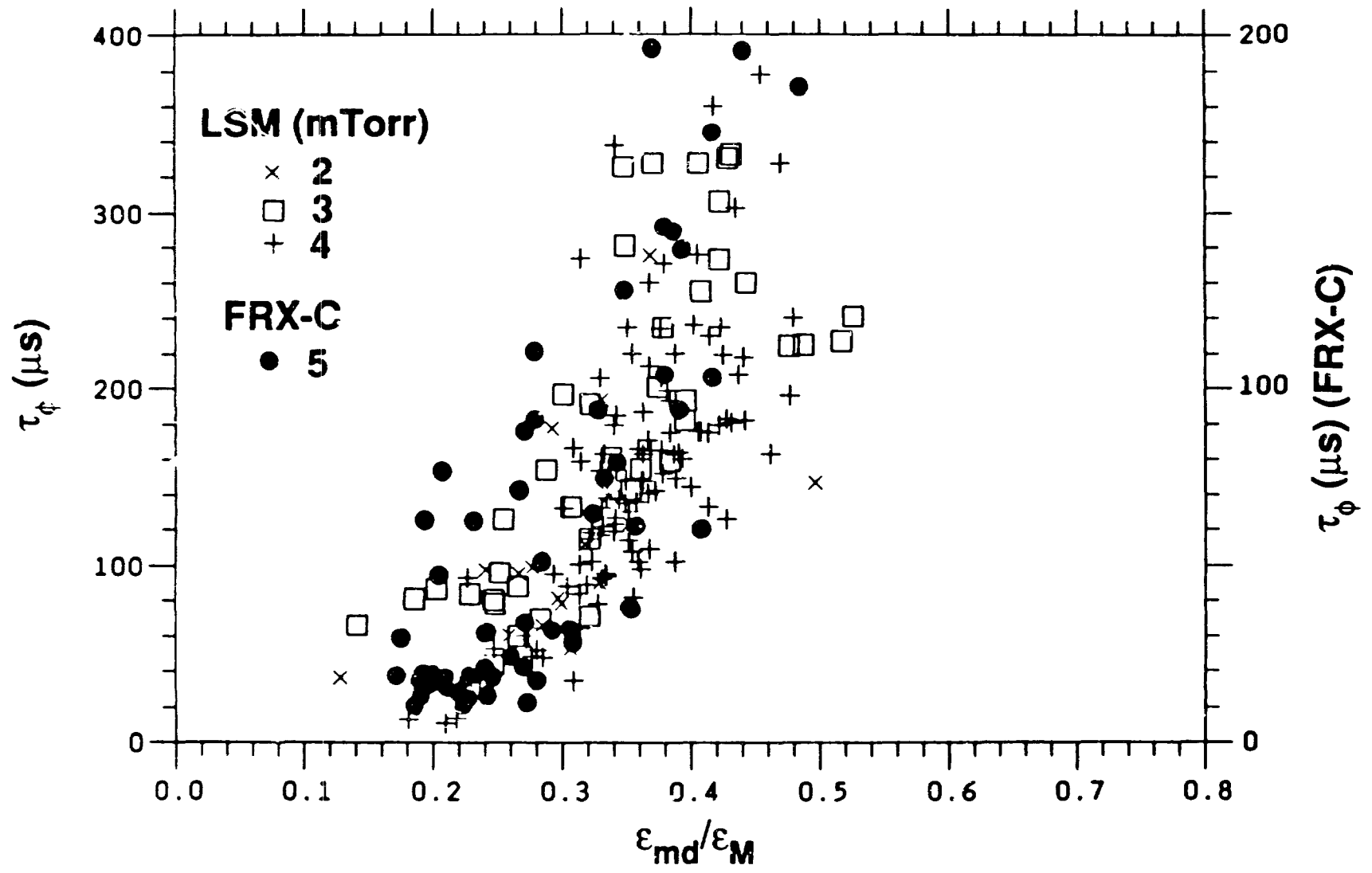
FIGURE CAPTIONS

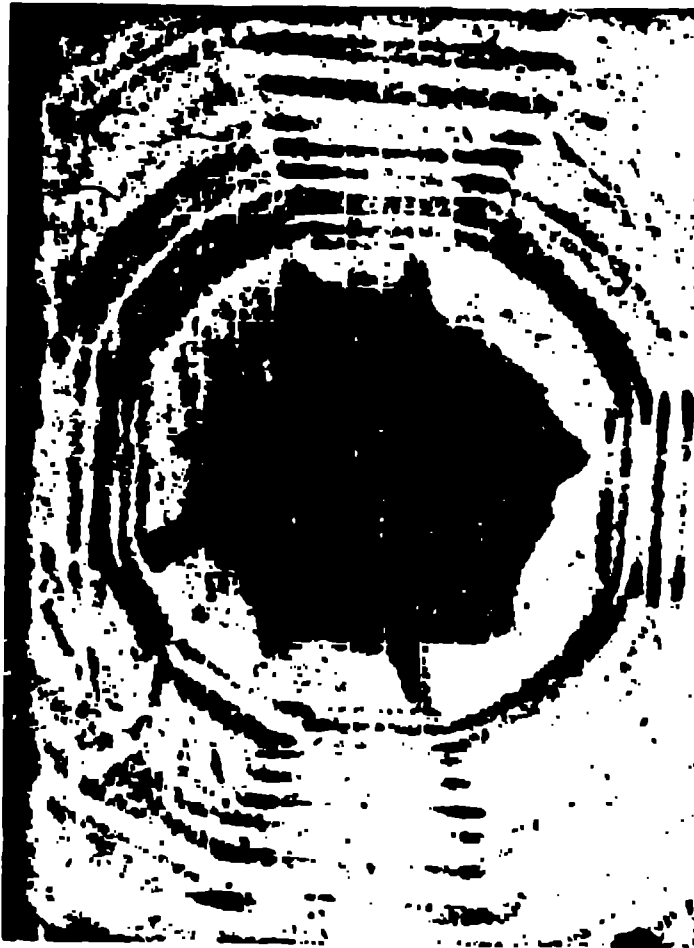
Fig. 1. Variation of flux confinement time τ_ϕ in FRX-C/LSM ($r_{\text{coil}} = 0.35 \text{ m}$) and FRX-C ($r_{\text{coil}} = 0.25 \text{ m}$) with inverse shock strength as measured by the minimum elongation of the $\int n d\ell$ profile, ϵ_{md} , normalized by an estimate of the initial elongation ϵ_M . The confinement times are plotted with different ordinate scales to remove the r_{coil}^2 dependence.

Fig. 2. End-viewing x-ray photographs of the FRC separatrix shape for (a) optimum 3 mtorr conditions at $t = 41 \mu\text{s}$ and (b) 5 mtorr conditions at $t = 6 \mu\text{s}$.

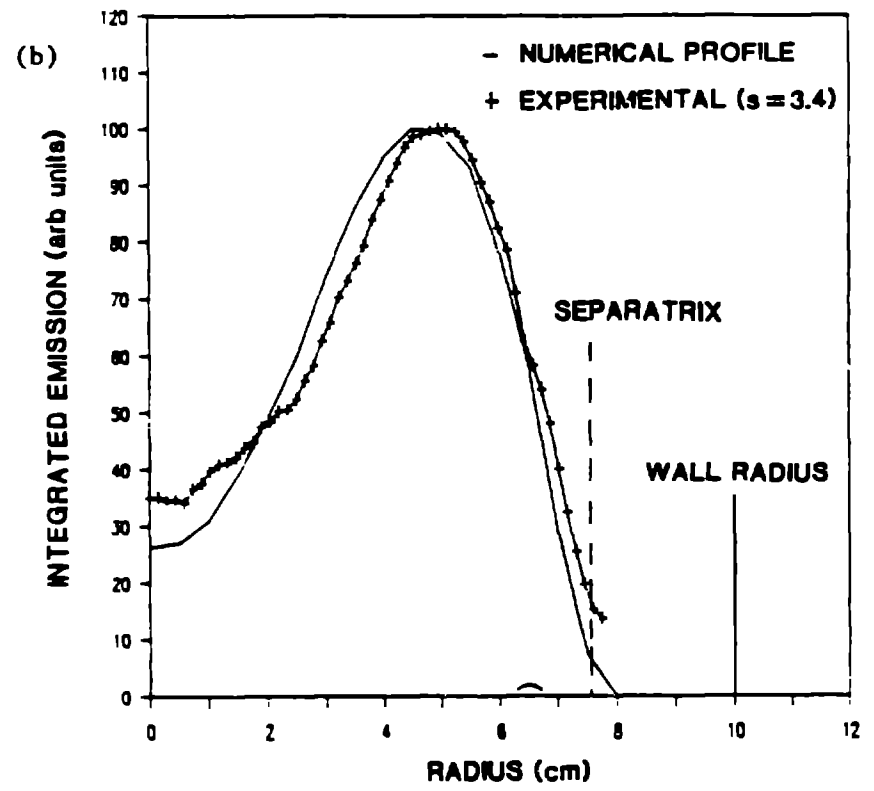
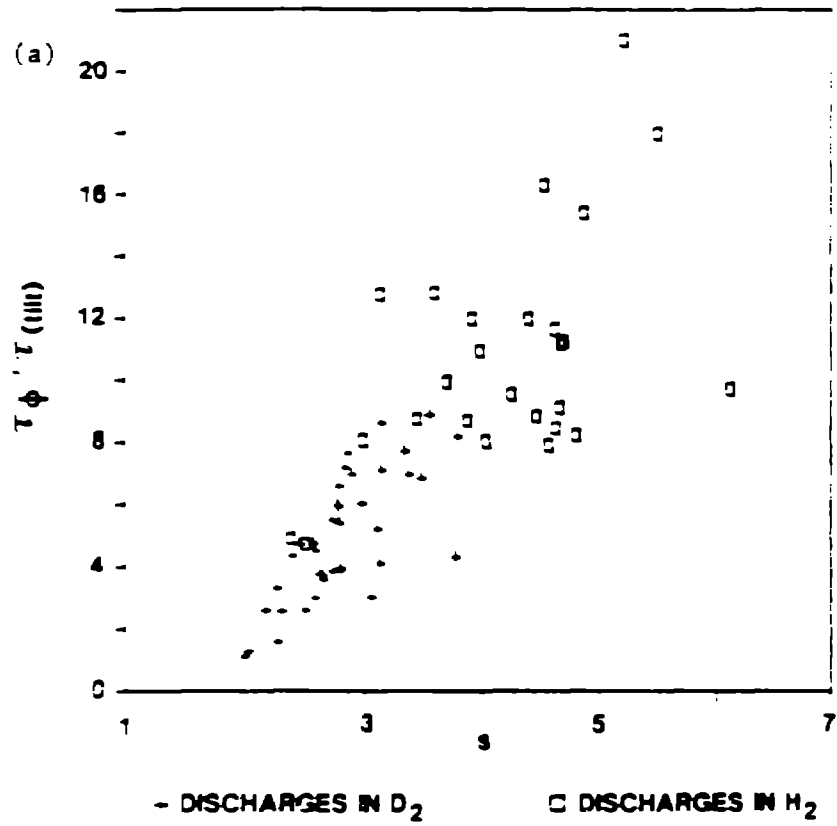
Fig. 3 (a) τ_ϕ normalized to the tilt growth time τ_{tilt} vs. s (s is average of first 20 μs). Discharges in D_2 are denoted by + and in H_2 by squares. (b) Axially integrated emission profiles. Numerical results are for a non-tilted FRC under similar conditions as in experiment.

Fig. 4. B_z vs t near the outer (upper curves) and inner (lower curves) coils at the CSS midplane. Numbers on curves are filling pressure in mTorr.





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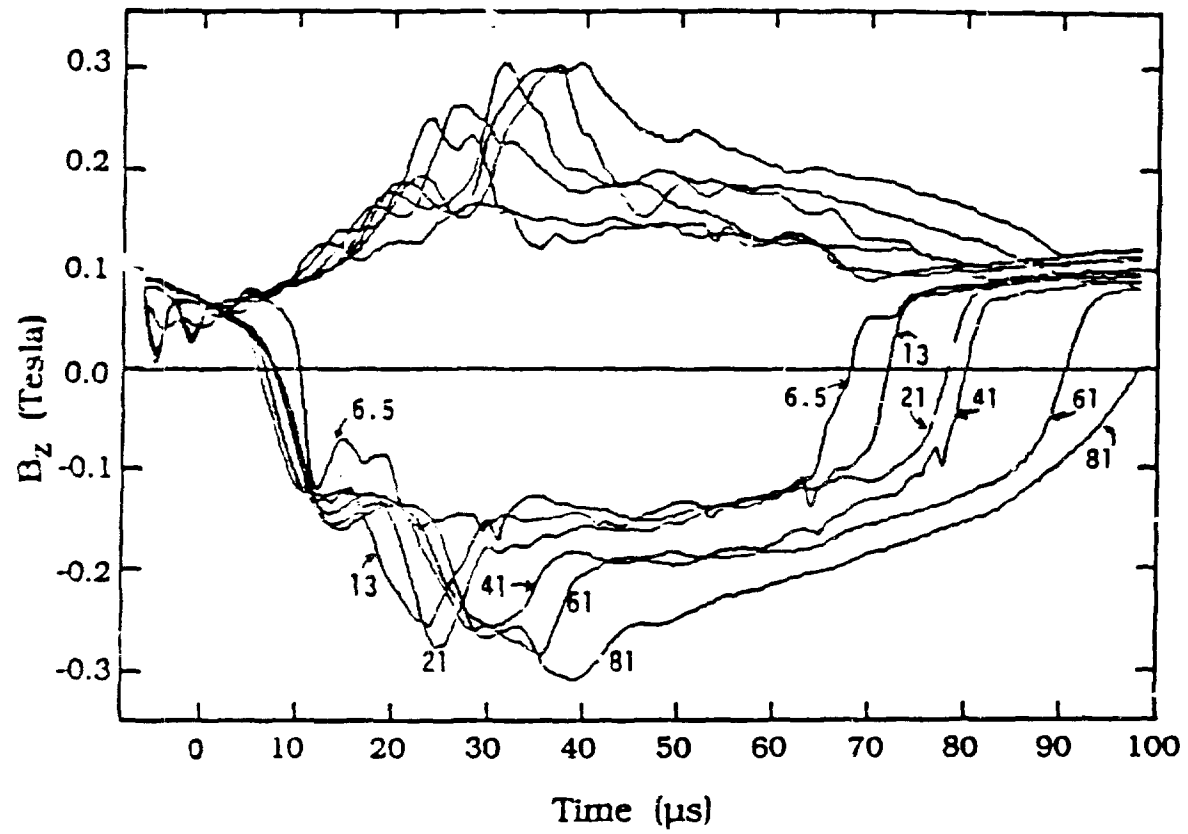


FIG. 4