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TITLE: RECENT FRC TRANSLATION EXPERIMENTS ON FRX-C/T

AUTHOR(S): D. J. Rej, W. T. Armstrong, R. E. Chrien, W. N. Hugrass,
P. L. Klingner, K. F. McKenna, E. G. Sherwood, R. E. Siemon,
and M. Tuszewski

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MASTER

Los Alamos
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

RECENT FRC TRANSLATION EXPERIMENTS ON FRX-C/T*

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Los Alamos National Laboratory, Los Alamos, NM, 87545

I. INTRODUCTION: Since the last CT Symposium,[1] several accomplishments have been realized from the FRC translation studies on the FRX-C/T device: (1) FRCs have been launched into, and trapped in, a dc magnetic guide field region without the use of any pulsed "gate" coils; (2) detailed studies of translation dynamics have been performed which are consistent with energy conservation, adiabatic compression theory, and 2-D MHD simulations; (3) the confinement properties of translated FRC has been evaluated; (4) translation through either puff or static deuterium gas fill has been demonstrated; (5) higher density ($n < 4 \times 10^{15}$ cm^{-3}) FRCs have been translated over 10-m lengths; (6) the $n = 2$ rotational instability has been stabilized by FRC translation into a weak helical quadrupole field.

II. APPARATUS: Since the last Symposium,[1] the FRX-C/T experiment has been modified (see Fig. 1). The translation region has been extended by 1.2 m in order to accommodate longer FRCs during the adiabatic decompression and confinement studies. The internal metallic cylinder (see Fig. 1 of Ref. 1) at the downstream end has been removed and the dc mirror field has been fortified to produce a peak field of up to 5.3 times the value B_o in the 3.7-m-long uniform field section of the translation region.

Diagnostics include: (1) an axial array of 52 magnetic probes positioned just inside the flux conserving walls; (2) six chords of interferometry; (3) bolometry; (4) soft x-ray detection; (5) VUV spectroscopy.

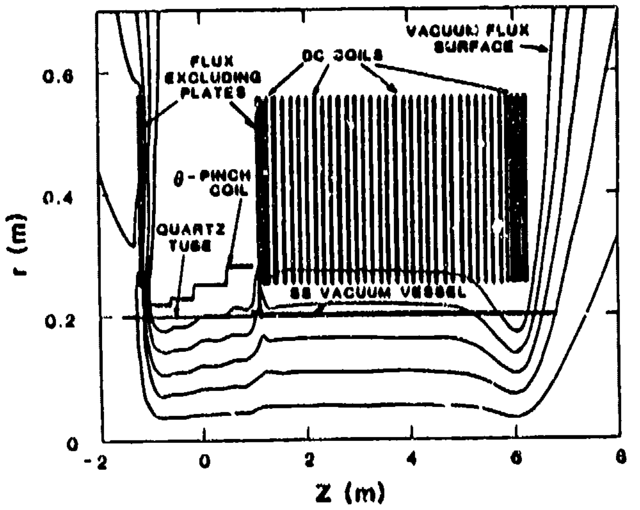


Figure 1: Schematic of FRX-C/T

III. TRANSLATION DYNAMICS: A variety of initial conditions in the θ-pinch source have been used (see Table I). The most extensive data base has been obtained for the 5-mtorr puff, low compression mode. These data have been reported elsewhere[2,3] and are only briefly reviewed here. FRCs are launched out of the θ-pinch approximately 15 μs after formation. The plasmas propagate 6 m at axial speeds v_z

Table I.

Observed plasma parameters in the FRX-C/T theta-pinch source for the five modes of operation.

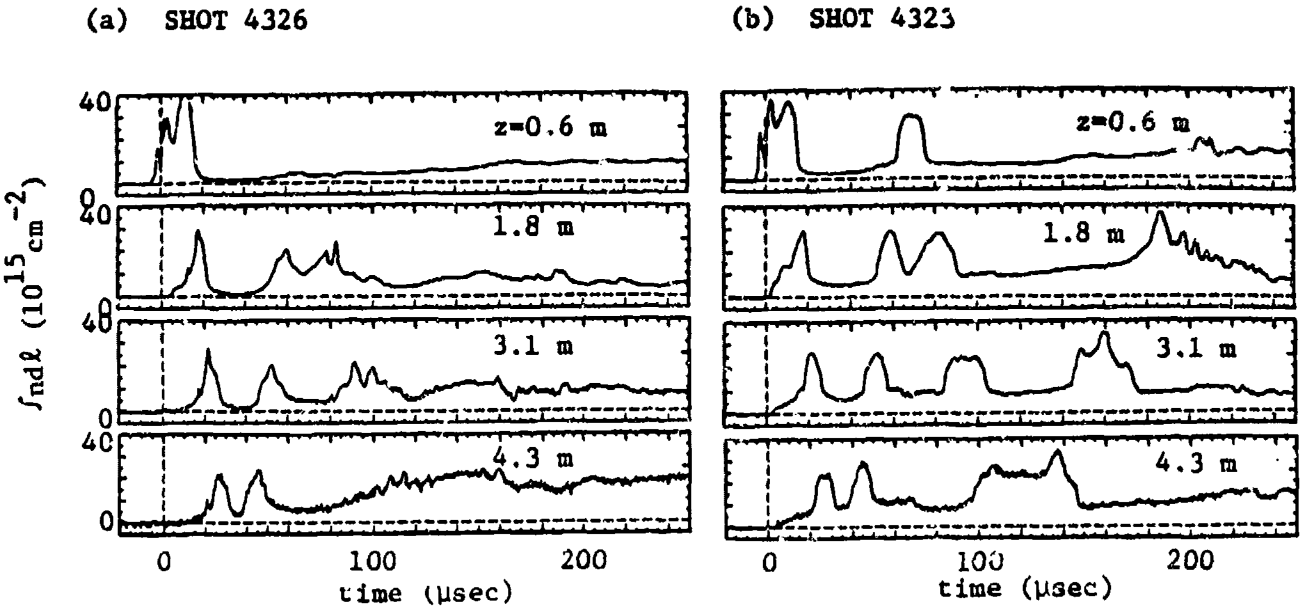
MODE	PLASMA PARAMETERS IN SOURCE	
	$\bar{n}_e$ (10^{15} cm^{-3})	$T_e + T_i$ (eV)
5 mtorr puff, low compression	1.4	575
5 mtorr puff, high compression	2.2	800
5 mtorr static, low compression	1.1	400
5 mtorr static, high compression	1.6	800
20 mtorr static, high compression	4.0	300

ranging between 25% and 100% of the ion thermal velocity ($\approx 2\times10^5$ m/s). The magnitude of v_z is adjusted by changing the guide field magnitude B_o. The FRCs reflect off the dc mirror downstream and propagate back toward the source at a reduced speed, only 0.7 times the incident speed (e.g., see Figs. 2, 3, and 6 in Ref. 2). Consequently, the FRCs do not have enough translational energy E_z to re-enter the source and they undergo a second reflection off the mirror field produced by the crowbarred θ-pinch coil. Another 50% reduction in E_z occurs during this reflection. In this manner, FRCs are readily trapped in the translation region without the aid of any additional pulsed "gate" coils. These FRC dynamics have been consistently modelled by 2-D MHD simulations.[2,3]

Plasma translation into a reduced guide field results in an expansion and cooling of the FRC. Good agreement in the scaling of n and T with B is obtained when one compares these data with the predictions of a reversible adiabatic compression theory. However, in the experiment, the plasma is observed to expand 15% more and cool 15% less than the theoretical expectations (e.g., see Fig. 4 of Ref. 2).

IV. CONFINEMENT: The energy, particle, and flux confinement of translated FRCs has been assessed using a measurement technique that capitalizes on the translation process.[4] For downstream mirror ratios up to 2.5, translation dynamics do not alter the FRC confinement. The energy confinement time $\tau_E \approx 100$ μs is obtained for plasma parameters: $n \approx 10^{15}$ cm^{-3}, $T_e + T_i \approx 0.7$ keV. This τ_E value is approximately 40% larger than that observed for similar non-translated FRCs in FRX-C. Bolometric measurements indicate that impurity radiation does not contribute appreciably to the energy confinement. The dominant contribution to τ_E is particle convection which can account in most cases for at least one-half of the global power loss. The confinement times, $\tau_N = 100 - 200$ μs, indicate anomalous transport and they are usually within a factor of two of those predicted from the lower-hybrid-drift (LHD) instability.[5] The observed empirical scaling, $\tau_N \propto x_s^{1.4} \ell_s^{0.2} n_M^{0.5} T^{0.4}$, however, differs from the LHD theory by weaker dependences on x_s and ℓ_s, and a more favorable dependence on T. This scaling is also consistent with data obtained on the TRX-1 experiment.[6] The poloidal flux loss is anomalous and the confinement times, $\tau_\phi = 100 - 200$ μs, are usually inferred. The observed empirical scaling, $\tau_\phi \propto x_s^{2.0} \ell_s^{-1.0} n_M^{0.2} T^{0.2}$, indicates a much weaker dependence on T than expected from classical theory (assuming T_e/T = constant).

V. STATIC FILL OPERATION: A puff gas injection system was developed for FRX-C/T in order to reduce the charge exchange losses downstream that were predicted to be appreciable if a static D_2 fill were used.[7] However, FRC translation experiments with a static fill were surprisingly good. From the side-on interferometry data (e.g., see Fig. 2b), one finds a substantial ionization (50 - 100%) of the 5-mtorr neutral gas background by the time of the FRC arrival. This ionization comes from two processes. First, a small ionization level is found through the entire translation region at early times. This ionization is attributed to high energy particles ejected from the source during the formation. Second, a more substantial ionization occurs just before FRC arrival, presumably from the open field line plasma that precedes the FRC. For comparison, interferometer data for a 5-mtorr puff discharge are shown in Fig. 2a.


(a) SHOT 4326

(b) SHOT 4323

FIGURE 2: Side-on interferometry data of a translating FRC with 5-mtorr (a) puff and (b) static fill. Interferometer chords are located at axial positions z = 0.6, 1.84, 3.05, and 4.27 m (see also Fig. 1).

Because of the significant preionization of the static fill, the energy and flux confinement properties (τ_E = 70 - 100 μs, τ_ϕ = 170 - 200 μs) are as good as (if not better than) with puff fill. The particle confinement time has not been determined because the decay of the particle inventory N is possibly influenced by refueling as the FRC moves through the background ionized gas. Values of -N/(dN/dt) increase from 100 - 200 μs with puff fill to 200 - 400 μs with static fill. The decrease in the particle inventory decay rate may, therefore, be explained either by an increase in τ_N or by refueling. The improvement in τ_N is conceivable because the large density gradient near the separatrix could be reduced by the substantial open field line plasma.

Another noteworthy observation is that with the static fill, the stable period τ_s, prior to the onset of the n = 2 instability, is approximately doubled over similar discharges with puff fill (see Fig. 2). Improved τ_N has been predicted to prolong τ_s.[8] Moreover, a significant amount of open field line plasma could also impede the transfer of rotational momentum to the FRC.

In summary, translation through a static fill does not degrade energy and flux confinement. Instead, it offers a mechanism to refuel an FRC and/or improve particle confinement.

VI. HIGH DENSITY OPERATION: FRC translation experiments have been executed using a 20-mtorr static fill. Plotted in Fig. 3 is the evolution of the excluded flux radius profile. The FRC moves at speed $v_z \approx 8$ cm/μs, a value that is about two times slower than in the 5-mtorr case because of the larger plasma mass at 20 mtorr. Partial tearing of this profile is observed as the plasma enters the translation region; however, MHD simulations[9] indicate that the downstream part of this "torn" profile is an

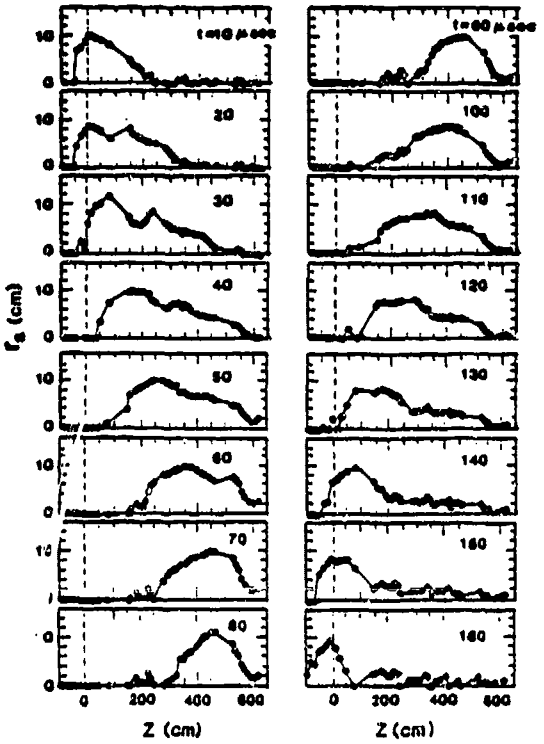


Fig. 3: Time evolution of the excluded flux radius profile for a single 20-mtorr discharge with B_0=4.5 kG.

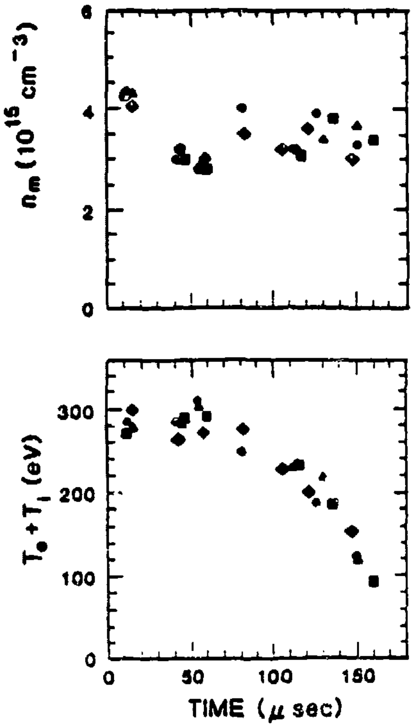
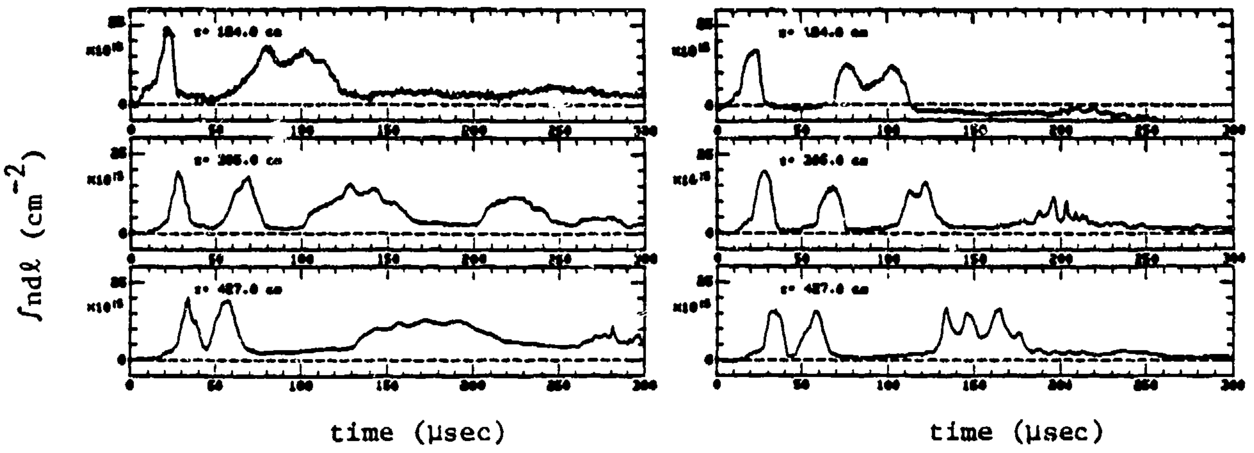


Fig. 4: Time evolution of maximum density and pressure balance temperature for four 20-mtorr discharges.

open field line plasma effect. The FRC reflects and translates back into the source because by the time the plasma reaches the source (t ≃ 150 μs), the crowbarred B-field in the θ-pinch coil has fallen sufficiently to create an antimirror to the dc guide field. The time dependent n_m and T values for four 20-mtorr discharges are plotted in Fig. 4. A 30% decrease in n_m occurs as the FRC accelerates and expands into the translation chamber. An increase in n_m to 3.8×10^{15} cm^{-3} occurs during the reflection (t ≃ 80 μs). A weaker oscillation of n_m is observed during the second transit, commensurate with the axial expansion and contraction of the separatrix. The confinement properties, $\tau_\phi \simeq 150$ μs and $\tau_E \simeq 100$ μs, are not degraded by the observed translation dynamics.

VII. n = 2 STABILIZATION EXPERIMENTS: Present translation experiments are directed toward stabilization of the n = 2 rotational instability. Weak helical quadrupole fields are known to stabilize this mode in non-translated FRCs.[10] In FRX-C/T, a helical quadrupole field is generated by coils wrapped around the translation region vacuum chamber with pitch angle $\alpha \simeq 6$ m^{-1}. Suppression of the n = 2 distortion is illustrated in Fig. 5 which displays interferometry data with and without the helical fields. Preliminary results indicate a threshold multipole toroidal field component at the separatrix of approximately 6% of the external B_z field is necessary to stabilize this mode. Stable configurations are observed for up to 300 μsec. Moreover, FRC trapping in the translation region is aided by an axial retarding force which results from the interaction of the FRC with the helical field. The effects of a straight quadrupole coil will be also explored in the near future.


(a) SHOT 5262

(b) SHOT 5263

Figure 4: Side-on interferometry data in the translation region of a translatir FRC with (a) a maximum helical quadrupole toroidal field component 0.2 kG at the separatrix, and (b) without quadrupole fields. Interferometer chords are at axial positions 1.84, 3.05, and 4.27 m.

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