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by

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ABSTRACT

A single-point Thomson scattering diagnostic is used to determine the electron temperature T_e of field-reversed-configuration (FRC) compact toroids generated in the θ -pinch source of the Los Alamos *FRX-C/LSM* experiment. Measurements are performed close to the axial midplane and near the magnetic and geometric axes. A broad range of plasma conditions is investigated and electron temperatures vary, on average, between 90 and 190 eV. For a given condition, T_e remains relatively constant during the 60 μ s measurement interval between formation and the onset of the $n=2$ rotational instability. T_e increases with plasma diameter and external magnetic field, and decreases slightly with fill pressure. The temperature at the geometric axis is consistently 10-20% lower than that near the field null. The temperature is approximately 35% higher than observed previously on the smaller *FRX-C* device. The implications of these measurements on plasma confinement properties are discussed.

I. INTRODUCTION AND SUMMARY

The electron temperature T_e is an important parameter for magnetically-confined fusion plasmas. Measurements of T_e often reveal significant phenomena that contribute to the physics of plasma confinement. The electron temperature has been of special interest in the understanding of the field-reversed configuration, an elongated compact toroid plasma that ideally contains no toroidal magnetic field. Previous measurements have indicated that the electrons are responsible for a substantial amount of power loss in present-day experiments, up to 80 MW or one-

third of the global loss.¹ When measured, radiation losses are found to be small,² leading one to speculate that non-classical, cross-field electron thermal conduction dominates. Electron energy confinement is a principal issue that will be addressed in upcoming high-power magnetic compression experiments at Los Alamos.³ The influence of the electron temperature on the poloidal flux confinement has been a long-standing issue. The electrical resistivity η inferred from flux loss is found to be anomalous, usually ranging between 3 and 20 times the classical Spitzer value;⁴⁻⁶ moreover, the classical scaling, $\eta \sim T_e^{-3/2}$, has never been confirmed, indicative of either non-classical resistivities or possible errors in assumptions on the time evolution of the equilibrium current density.⁷

In this report, we present detailed electron temperature data from single-point Thomson scattering measurements of FRCs formed and trapped *in situ* on the Los Alamos *FRX-C/LSM* (*LSM*) field-reversed θ -pinch. These experiments mark the first comprehensive FRC T_e measurements in over five years. Data have been collected on over 400 discharges during a four-week period beginning in October 1988. Measurements have been made close to the axial midplane and at either of two radii, near the field null or at the geometric axis.

The electron temperature depends on the measurement radius and on the plasma condition. T_e values, on average, vary between 90 and 190 eV. Both the shot-to-shot variations and the measurement error are typically 10% to 20%. As in earlier experiments on the smaller FRCs of *FRX-B*⁸ and *FRX-C*,¹ the electron temperature is found to remain relatively constant in time during the period between formation and the onset of the $n=2$ rotational instability.

The electron temperature increases with trapped flux ϕ_p . With a 3-mtorr initial deuterium fill pressure and a 0.4-T external B-field, the inferred ϕ_p increases from 1.0 to 7.5 mWb when the reversed bias magnetic field is increased from 37 to 95 mT. The plasma separatrix radius r_s and T_e near the field null increase from 0.11 m to 0.18 m and 120 to 190 eV, respectively.

There is a weak dependence on the initial fill pressure p_0 . T_e near the field null decreases from 160 to 140 eV when p_0 is increased from 2 to 4 mtorr, while remaining essentially constant at the geometric axis. There is also a weak dependence on the external magnetic field B_w . A 10% increase in T_e is observed when B_w is increased by 35%.

Linear θ -pinch configurations have been generated without the bias field. Electron temperatures are almost two times smaller than those measured in FRCs,

consistent with the large thermal conduction losses characteristic of open-field-line configurations.

The temperature at the geometric axis is 7% to 20% lower than at the field null. This observation implies a relatively flat $T_e(r)$ profile inside the separatrix, similar to that found in previous experiments.

When compared to earlier measurements on smaller FRC plasmas produced in *FRX-C*,¹ the electron temperature in *LSM* is found to be higher by approximately 35%. There are no clear indications of increased electron heating during the formation phase on *LSM*; furthermore, the heating rate during the equilibrium phase after formation has decreased. During equilibrium, the largest source of power input to the electron continues to be from classical equilibration with ions, but at substantially reduced rates compared to *FRX-C*. The higher T_e and the decreased heating imply improved electron energy confinement times on *LSM*.

The fractional contributions to the global energy confinement have remained essentially unchanged from *FRX-C*. Particle diffusion dominates while the remaining 20 to 40% of the losses are attributed to nonconvective processes by electrons.

Under the assumption that all nonconvective electron losses are from thermal conduction, transport coefficients are inferred by both dimensional analysis and with a 1½-dimensional transport code. Even for conditions with optimum confinement, the average cross-field thermal diffusivity is anomalous, $\chi_{\perp e} \approx 160 \text{ m}^2/\text{s}$, which corresponds to 35 times the classical value.

There is no clear correlation between confinement and the electron temperature. In particular, there is no improvement in the inferred poloidal magnetic flux confinement time τ_ϕ even when the classical scaling factor $r_s^2 T_e^{3/2}$ is increased by almost an order of magnitude. Also, no obvious correlations are evident when data are compared with a Bohm-like scaling BR^2/T_e predicted from low-frequency drift instability theory.⁹

II. APPARATUS AND EXPERIMENTAL CONDITIONS

Experiments were performed on the *FRX-C/LSM (LSM)* facility.¹⁰ As illustrated in Fig. 1, the front end consisted of a straight 0.70-m-i.d., 2.0-m-long field-reversing θ -pinch coil. Auxiliary "cusp" coils mounted at each end provided a quasi-static B-field in the direction of the main θ -pinch field; these coils produced end-cusps before field reversal to insure non-tearing formation, and mirror fields to confine the

FRC after reversal. Plasmas were formed and trapped in the θ -pinch source. The 0.40-m-i.d., 6.7-m-long stainless-steel translation chamber, however, remained attached to the source during these experiments.

The electron temperature was measured at a single point in space and time on each discharge. The Thomson scattering diagnostic included a Q-switched ruby laser ($\lambda_c = 694.3$ nm, 20-ns pulsewidth, 13-mm diameter, 3-mrad divergence, 5-J output energy) focused from one end to a point 0.2 m from the axial midplane of the θ -pinch coil and at a radius of either 0.00 or 0.10 m (see Fig. 1). Scattered light was collected, dispersed and detected with a 7-channel, triple-grating polychromator similar to the one used on the *Scylla-IVP* θ -pinch experiment.¹¹ The polychromator was configured to detect light wavelengths between 658 and 692 nm. Photomultiplier currents were measured with gated analog-to-digital converters (LeCroy model 2249). Plasma background signals were recorded 100 ns before and 100 ns after the laser pulse. Data were processed and T_e was determined immediately after each discharge with a Prime model 750 computer. Data from an *LSM* discharge are plotted in Fig. 2.

Other "on-line" diagnostics operational during this data run included an excluded-flux array used to measure the axial profile of the separatrix radius $r_s(z)$, and a single-chord interferometer aligned to measure $\int n dl$ across the diameter at the axial midplane $z=0$. In addition, a new 7-chord instrument positioned at $z=0$ was being checked out during a portion of this data run. An image-intensifying streak camera was positioned side-on to monitor radial motion of the plasma column near the axial midplane. Two ion temperature diagnostics, a polychromator tuned to detect the 227.1-nm CV line and a time-integrated neutron detector, were also installed on the experiment.

Electron temperatures were measured at both radial positions during the time interval $10 \leq t \leq 70 \mu s$ between FRC formation and the onset of the $n=2$ instability which usually terminated the discharge. A variety of plasma conditions were produced by adjusting three external parameters: (1) the initial deuterium fill pressure p_0 ; (2) the reversed bias magnetic field B_b ; and (3) the external equilibrium magnetic field B_w . The fill-pressure scan was performed at $B_b \approx 60$ mT and $B_w \approx 0.4$ T (at time $t = 30 \mu s$) with p_0 set at either 2, 3, 4 or 5 mtorr. The bias-field scan, $37 \leq B_b \leq 95$ mT, was performed at 3 mtorr and $B_w \approx 0.4$ T. There were also limited measurements at 5 mtorr and large bias, $B_b \approx 100$ mT, a condition where in earlier experiments a soft x-ray diagnostic revealed large flute-like

distortions of the plasma column.⁶ B_w could be varied by adjusting the capacitance of the main θ -pinch bank. At $p_o = 3$ mtorr and $B_o \approx 65$ mT, B_w was increased from 0.4 T to 0.6 T.

III. EXPERIMENTAL OBSERVATIONS

A. Fill Pressure Scan

As the fill pressure was increased from 2 to 5 mtorr, with bias and external B-fields kept constant, colder, higher-density FRCs were produced. The experimental conditions and the plasma parameters are listed in Table I; each value represents an average of many discharges, while its uncertainty denotes the standard deviation. For each fill pressure, the bias magnetic field and the timing between the θ -pinch preionization (PI) and main capacitor bank discharge were tuned to values that previously led to optimized confinement times.⁶ The plasma parameters quoted in Table I were measured at time $t = 30 \mu\text{s}$, while the time-averaged flux, energy, and particle confinement times (τ_ϕ , τ_E , and τ_N) were obtained with a 0-D transport model.^{5,12} For all fill pressures, the separatrix radius r_s remained relatively constant at 0.16 ± 0.01 m. The corresponding field-null radius, $R \approx 0.11$ m, was inferred from the equilibrium relationship, $R = r_s/\sqrt{2}$, derived for an elongated FRC.⁸ [Note: For the remainder of this report, the T_e measurements performed at $r = 0.10$ m will be quoted as that near the field null $r \approx R$.] The FRC confinement times were sufficiently long for most fill pressures, $p_o \leq 4$ mtorr, for one to confidently believe that an FRC equilibrium existed. At 5 mtorr, however, the short confinement times cast some doubt on the true nature of the plasma configuration. Further discussion of the FRC confinement properties can be found in Section IV.

Electron temperatures at each fill pressure and radial position are plotted against time in Figures 3 through 6. The main θ -pinch capacitor bank was discharged at time $t = 0$. Each data point corresponds to a separate discharge while its error bar denotes the uncertainty in the Gaussian fit. For all cases except 5 mtorr, a handful of shots with very poor confinement, $\tau_\phi < 75 \mu\text{s}$, have been excluded from these $T_e(t)$ plots.

To within the experimental error and shot-to-shot scatter, the electron temperature remained constant in time. The time and shot averaged temperatures for each condition are listed in Table II. In computing the average T_e , equal weight

was given to each data point, regardless of the error in the Gaussian fit. The uncertainties quoted in Table II correspond to the standard deviation of the computed average. For reference, an average ion temperature T_i at $t = 30 \mu\text{s}$ is quoted. T_i was obtained from the difference between pressure balance temperature at $t = 30 \mu\text{s}$ and the field-null T_e .

From the data in Table II, one observes that the average field-null electron temperature decreased by 15% when the fill pressure was increased from 2 to 4 mtorr. T_e at the geometric axis, on the other hand, remained relatively constant at 133 eV. For all cases except $p_0 \approx 5$ mtorr, the inferred ion temperature at $r=R$ and $t = 30 \mu\text{s}$ was 2 to 3 times larger than T_e .

B. Bias Field Scan

The most extensive reversed-bias-field scan was performed at $p_0 = 3$ mtorr, with $B_w = 0.41 \pm 0.04$ T, and PI timing of $18.6 \pm 0.1 \mu\text{s}$. The bias field B_b was varied between 37 and 95 mT, an operation range where reasonably-long configuration lifetimes were observed. The electron temperature was measured immediately after formation of the FRC equilibrium, at time $t = 30 \mu\text{s}$.

As illustrated in Figure 7, when the bias flux was increased, more poloidal flux was measured both at field reversal and in the FRC equilibrium. Typically, 35 to 65% of the initial bias flux remained accounted for during the "zero crossing" (i.e., at time $t=0$ when the magnetic field reverses at the wall). Approximately 30 to 60% of the zero-crossing flux was trapped in the equilibrium FRC, consistent with the predictions of a semiempirical formation model.¹³ Consequently, the FRC separatrix radius increased with B_b from 0.10 to 0.19 m (see Fig. 8). Other plasma parameters also varied. As indicated by the data points in Figure 9 and from the shot averages in Table III, larger-diameter plasmas were hotter, less dense, shorter, and contained a larger particle inventory (up to 80% of the initial fill) at $t = 30 \mu\text{s}$.

The electron temperature, on average, also increased with the plasma diameter. The data plotted in Figure 10 reveal a 90% increase in the upper bound of $T_e(r=R)$ when r_s was increased by 60%. Unweighted shot averages of the same data are plotted in Figure 11. Logarithmic least-squares fits to these data yielded the empirical scaling,

$$T_e(r=R) \approx 13 r_s^{0.92}$$

$$T_e(r=0) \approx 10 r_s^{0.94} ,$$

where T_e is in eV and r_s is in cm. The inferred ion temperature at $t = 30 \mu s$ did not change significantly, as illustrated by the data in Figure 12; however, the average T_i showed the weak empirical scaling,

$$T_i(r=R) \approx 143 r_s^{0.33} .$$

A few discharges were made at higher bias fields, $B_b = 96$ mT, conditions where poor confinement ($\tau_\phi \leq 60 \mu s$) was consistently observed. The measured temperature, $T_e \approx 175$ eV, did not differ discernibly from that observed in the better-confined FRCs at lower bias field.

A few high-bias discharges were obtained at 5-mtorr fill pressure, conditions where the soft x-ray diagnostic revealed high toroidal mode number perturbations at the plasma edge. For $B_b = 92$ mT, the typical plasma parameters at $30 \mu s$ were $B_w \approx 0.4$ T, $r_s \approx 0.17$ m, $\phi_p \approx 5$ mWb, $\langle n \rangle \approx 9 \times 10^{20} \text{ m}^{-3}$, $T_e + T_i \approx 400$ eV. The confinement times were poor: $\tau_\phi \approx 31 \mu s$, $\tau_N \approx 52 \mu s$, $\tau_E \approx 27 \mu s$. The average electron temperatures were 128 ± 12 eV at $r \approx R$ and 118 ± 16 eV at $r=0$. The T_e values were not appreciably different from the low-bias case (see Table I) but larger than those of open-field-line plasmas (see below).

C. Equilibrium Field Scan

To date, the best flux trapping and confinement parameters on *LSM* were obtained at reduced plasma energy densities and external field B_w . The data presented in the above sections were obtained at these "degraded" conditions. In this section, we present results obtained with larger B-fields corresponding to the operation of the entire main θ -pinch capacitor bank. Experiments were performed at 3-mtorr fill pressure and modest bias fields, $B_b = 65$ mT. The changes in FRC parameters that resulted from the 40% increase in B_w are listed in Table IV. In general, the higher-field plasmas were smaller, more dense, hotter, contained less flux, and had poorer confinement. The density and pressure-balance temperature increased as expected from the adiabatic compression theory scaling,¹⁴ $n \sim B_w^{6/5}$ and $T \sim B_w^{4/5}$.

The electron temperature showed a modest increase with B_w . T_e at $r \approx R$ and $r=0$ for the high-field case are plotted in Figure 13. As observed at low B_w , the temperature remained constant in time, to within the scatter. Shot and time-averaged temperatures are quoted in Table V. The average T_e increased by 10 to 15% which was less than both the standard deviation (20%) and the prediction from adiabatic theory (27%).

A noteworthy feature of the data at $r=0$ in Figure 13 is the large magnitude of the error bars, which usually exceeded the shot-to-shot scatter in T_e . The fitting error for this case was consistently larger than for every other condition investigated; however, there were systematic features. As illustrated by the representative data in Figure 14, the scattered signal consistently deviated from the expected Gaussian, appearing more like a two-temperature distribution.

D. Open-Field Configurations

It is interesting to compare the FRC with the linear θ -pinch configuration. These open-field-line configurations were generated on *LSM* by operating without the reversed bias field. During the Thomson scattering run at $r=0$, with $B_w = 0.33$ to 0.43 T and $p_0 = 3$ and 4 mtorr, a few linear θ -pinch discharges were made. For all cases, a small plasma column with an excluded flux radius of 0.10 m formed and decayed away rapidly, typically in $30 \mu\text{s}$. The electron temperature of 85 ± 10 eV was consistently less than that in an FRC formed with similar PI and B_w .

IV. HEATING AND CONFINEMENT

In this section, the Thomson scattering data are interpreted. Power flow in the electron channel is studied and transport coefficients are estimated by both dimensional analysis and with a 1½-dimensional transport code. The contributions of electron losses to the global power balance are assessed. The effect of the electron temperature on the poloidal flux confinement is also considered.

When compared to the smaller FRCs produced in *FRX-C*, the electron temperature in *LSM* is about 35% higher. For example, the plasma density and magnetic field produced at 4 mtorr in *LSM*, $n \approx 1.1 \times 10^{21} \text{m}^{-3}$ and 0.45 T with $r_s \approx 0.17$ m (see Tables I and II), are virtually identical to those measured on *FRX-C* at "degraded" 5 -mtorr conditions with $r_s \approx 0.12$ m.¹⁵ The electron temperature near

the field null is 140 eV on *LSM* and only 105 eV on *FRX-C*. There exist two plausible reasons for the higher electron temperature: (1) more heating; and/or (2) better confinement. These explanations are further explored in the analysis below.

A. Electron Heating

Electron heating occurs in two distinct phases, during and after FRC formation. A semi-empirical formation model¹³ has been used to estimate the heating source terms. Given the size of the liftoff flux, the azimuthal electric field, and the fill pressure, this model can predict the FRC total temperature T after formation; moreover, it can estimate the relative magnitudes of two different sets of heating mechanisms: (1) radial shock and compression; and (2) the combination of axial shock and resistive annihilation of reversed magnetic flux. As an example, we compare the same 4-mtorr *LSM* and degraded 5-mtorr *FRX-C* cases considered in the preceding paragraph. As demonstrated in Ref. 13, the model correctly predicts the inferred temperature, $T \approx 430$ eV. On *FRX-C*, resistive and axial heating appears to be equally important as radial heating. For the 4-mtorr *LSM* case, radial heating dominates, accounting for 75% of the plasma energy. The difference between the two experiments can be attributed to a higher normalized liftoff flux, $G_{LO} = 0.28$ on *FRX-C* as compared with 0.17 on *LSM*. Unfortunately, the formation model does not predict how the formation energy is divided between electrons and ions. While there is no theoretical basis for more electron heating on *LSM*, one might speculate that there should be less. Classically, one expects most of the shock energy to be deposited to the ions, resistive heating to the electrons, and the compression heating given by the adiabatic laws subject to initial conditions and ion-electron equipartition. In this "classical" context, one would expect a higher T_e on *FRX-C* and a higher T_i on *LSM*. These expectations are contrary to observations, indicating that the higher temperatures on *LSM* cannot be explained by increased heating during formation; however, this conclusion is weak since the classical picture is probably not a realistic description of the turbulent FRC formation process.

It is somewhat easier to understand FRC energy balance during the decay phase after formation. Electrons are heated by at least three sources: (1) Coulomb collisions with hotter ions; (2) magnetic compression; and (3) ohmic heating. The electron heating rate due to Coulomb collisions with ions is

$$dT_e/dt = (T_i - T_e)/\tau_{eq} \quad , \quad (1)$$

with the energy equilibration time between deuterons and electrons,¹⁶ $\tau_{eq} = 6.3 \times 10^{14} T_e^{3/2}/n \ln \Lambda_{ei}$ [units: μs , eV, and cm^{-3}], where $\ln \Lambda_{ei}$ is the Coulomb logarithm which is about 12 for *LSM*. The equilibration time near the field null typically ranges from 80 to 200 μs , depending on conditions. The average equilibration heating rates at $r \approx R$ computed from Eq. 1 are listed in Table VI. Comparing *FRCs* with comparable density and B-field, one finds that the power flow from electron-ion equilibration on *LSM* is more than two times smaller than on *FRX-C*. Nevertheless, equilibration usually accounts for most of the input energy to the electrons. Values range from 1.2 eV/ μs at 3 mtorr, large bias, and low external field, to 3.4 eV/ μs at low bias and high field. The relatively large standard deviations reflect the shot-to-shot variations in $T_e^{3/2}$.

The power to electrons from adiabatic magnetic compression can be estimated by the equation¹⁴

$$dT_e/dt = 2T_e/3\tau_v \quad , \quad (2)$$

where $\tau_v = -V_s/(dV_s/dt)$ is the characteristic decay time of the separatrix volume V_s . Typically, τ_v varies between 2 and 4 times the global energy confinement time τ_E . The compression heating rate ranges between 0.3 and 2 eV/ μs , depending on conditions (see Table VI). For all cases except $p_0 = 5$ mtorr, the compression power is relatively small, less than one-half of the equilibration input power.

The ohmic power input to the plasma is given by the relationship⁵

$$d(T_e + T_i)/dt = (T_e + T_i)/\tau_\Omega \quad , \quad (3)$$

where $\tau_\Omega = 3\langle\beta\rangle\tau_\phi/4(1-\langle\beta\rangle)$. From Eq. 3, the ohmic heating rate near the field null is estimated at 0.5 to 2 eV/ μs . Because of the anomalous resistivity inferred from flux loss (see below), a sizable fraction of this power can go to the ions. As done previously,⁵ the fraction to electrons is assumed to be $0.3 \times (1 + T_e/T_i)$ ($\approx 42\%$ on *LSM*), consistent with lower-hybrid-drift turbulence. Values based on

this model are listed in Table VI. The ohmic heating rate to electrons at $r \approx R$ is typically 0.2 to 0.3 eV/ μ s; larger rates are inferred for conditions with short τ_ϕ (5 mtorr) or large ϕ_p (3 mtorr, high bias).

B. Electron Energy Confinement

During the equilibrium phase after formation, the electron energy balance is given by the equation

$$(3/2) d(NT_e)/dt = P_{in} - P_{Ne} - P_{Ee} \quad , \quad (4)$$

where N is the electron inventory inside the separatrix, and P_{in} represents the integrated input power to the electrons due to ion-electron equilibration, compression, and ohmic dissipation, while P_{Ne} and P_{Ee} represent losses due to particle diffusion and "nonconvective" processes (e.g., thermal conduction, ionization, and/or radiation), respectively. Electrons diffuse across field lines and escape from the system, each carrying away an energy $(5/2)T_e$; ¹⁷ therefore, the "convective" electron power loss can be estimated by the equation

$$P_{Ne} \approx (5/2)NT_e/\tau_N \quad . \quad (5)$$

After substituting the relationship, $dN/dt = -N/\tau_N$, Eq. 4 reduces to a simpler form,

$$(3/2) N(dT_e/dt) \approx P_{in} - NT_e/\tau_N - P_{Ee} \quad . \quad (6)$$

In our analysis, we restrict ourselves to low-bias conditions where the electron temperature has been measured against time (cf. Figs. 3-5 and 13) and found to be relatively constant, i.e., $dT_e/dt \approx 0$. The average powers P_{in} , P_{Ne} , and P_{Ee} for these conditions are listed in Table VII. P_{in} is found by integrating and summing the electron heating rates of Table VI. P_{Ne} is computed from Eq. 5 with the experimental τ_N determined from the 0-D analysis of interferometer and excluded flux data. P_{Ee} is then computed from the difference $P_{in} - NT_e/\tau_N$.

From the data in Table VII, one finds that P_{in} is substantial, ranging between 40 and 80 MW. The nonconvective and convective electron power losses are comparable. The losses have been also compared to the total power loss from the plasma, $P_{tot} = (3/2)N(T_e + T_i)/\tau_E$, which is determined from 0-D analysis of the excluded flux data. P_{Ee} ranges from 21% of P_{tot} at 2 mtorr to 38% at 4 mtorr. As in earlier studies, particle diffusion still dominates the global energy confinement. The total convective power loss from electrons and ions, $P_{Ne} \times (1 + T_i/T_e)$, accounts for at least 60% of P_{tot} in all cases.

In the experimental limit where $dT_e/dt \approx 0$, the nonconvective electron energy confinement time τ_{Ee} is given by the relationship, $\tau_{Ee} \approx (3/2)NT_e/P_{Ee}$. From the data in Table VII, τ_{Ee} is estimated to be approximately 100 μs for the 2 and 3 mtorr cases and 65 μs for 4 mtorr. These confinement times are better than on *FRX-C* from which τ_{Ee} values as low as 33 μs can be inferred.⁵

A variety of effects might be responsible for the large nonconvective electron power loss, P_{Ee} . Possible candidates are ionization, radiation, or thermal conduction. Ionization losses have never been measured in an FRC but have been estimated to be small,¹⁸ in view of the comparatively low neutral flux and very short mean free path in the sheath plasma outside the separatrix. Radiation losses have not been measured on *LSM*; however, earlier bolometer measurements² on *FRX-C/T* indicated that radiative losses are small, accounting for 7% of P_{tot} . By the process of elimination but without experimental verification, the relatively large magnitude of P_{Ee} is often attributed to cross-field thermal conduction.

We now further pursue the speculation that P_{Ee} is entirely due to electron thermal conduction radially outwards across magnetic field lines. Dimensional analyses in the paragraphs below are followed by a more detailed computation with the 1½-D transport code in Section IV.D. Previous Thomson scattering measurements on *FRX-C* indicated that the electron temperature at the separatrix is the same as at $r=0$, consistent with our expectation that T_e is constant on flux surfaces; therefore, for the remainder of this report, we will assume separatrix temperatures equal to those actually measured at the geometric axis.

The electron heat flux q due to thermal conduction for the elongated FRC is given by the equation

$$q = \kappa_{\perp} dT_e/dr \quad . \quad (7)$$

A crude estimate of the electron cross-field thermal conductivity $\kappa_{\perp}$ can be made from a dimensional analysis. Assuming that the nonconvective power loss is uniformly distributed over the separatrix area, $A_s = \pi r_s^2$, and that there is a linear temperature profile across the minor radius, $a = r_s - R$, one can rewrite Eq. 7 as

$$\kappa_{\perp} \approx P_{Ee} a / \Delta T_e A_s \quad , \quad (8)$$

where $\Delta T_e = T_e(R) - T_e(r_s)$. The $\kappa_{\perp}$ values predicted by Eq. 8 range from $1.6 \times 10^{23} \text{ m}^{-1}\text{s}^{-1}$ at 2 mtorr to 7.5×10^{23} at 4 mtorr (see Table VIII). The corresponding perpendicular electron thermal diffusivity, $\chi_{\perp} = \kappa_{\perp} / n$, varies between 250 and 715 m^2s^{-1} .

The inferred electron thermal conductivity can be compared to the classical value $\kappa_{\perp c}$, which is given by¹⁶

$$\kappa_{\perp c} = 4.7 n T_e / m_e \omega_{ce}^2 \tau_{ee} \quad . \quad (9)$$

Using the average measured values of n and T_e and the average B between R and r_s computed from the rigid-rotor equilibrium profile, $\kappa_{\perp c}$ has been computed using Eq. 9 and found to be significantly smaller than the above experimental values (see Table VIII). $\kappa_{\perp} / \kappa_{\perp c}$ varies from 54 at 3 mtorr and low field to 140 at 4 mtorr. These numbers may be compared to earlier *FRX-C* measurements¹ at full-field 5 mtorr, where $n \approx 1.9 \times 10^{21} \text{ m}^{-3}$, $B_w \approx 0.8 \text{ T}$, $r_s \approx 0.10 \text{ m}$, $T_e(R) \approx 175 \text{ eV}$, $T_e(r_s) \approx 150 \text{ eV}$, and $\kappa_{\perp} / \kappa_{\perp c} \approx 80$. While anomalous, the inferred $\kappa_{\perp}$ remains four orders of magnitude smaller than the classical value along magnetic field lines, $\kappa_{\parallel c} = 3.2 \times n T_e \tau_{ee} / m_e$ (see Table VIII).

The *LSM* $\chi_{\perp}$ values may at first seem large, especially when they are compared to those obtained from other plasma configurations. For example, $\chi_{\perp}$ typically ranges between 0.2 and 10 m^2s^{-1} in tokamaks.¹⁹ It should be noted, however, that the classical diffusivities in these higher-field, less-collisional devices are significantly smaller than for the FRC; consequently, the anomaly factors for tokamaks are enormous. As an example, we consider ohmic discharges in the *JET* tokamak, in which a minimum $\chi_{\perp}$ of 0.2 m^2s^{-1} was reported.²⁰ For discharges where $T_e \approx 5 \text{ keV}$, $n \approx 3 \times 10^{19} \text{ m}^{-3}$, and $B \approx 2.8 \text{ T}$, the classical thermal diffusivity is estimated to be $6 \times 10^{-4} \text{ m}^2\text{s}^{-1}$. The corresponding thermal conduction anomaly

factor is over 300. This anomaly grows by more than an order of magnitude for auxiliary-heated discharges on *JET*, where $\chi_{\perp}$ values of $2.5 \text{ m}^2\text{s}^{-1}$ were reported.²¹

The FRC electron temperature is approximately twice that measured in open-field-line configurations (*cf.* Section III.D). The heating terms for the equilibrium FRC are no greater than for the open configuration; therefore, one can conclude that the closed field lines improve the electron energy confinement. The measured T_e values for the FRC are consistently larger than the predictions of two theories based on open-field-line electron energy confinement. The first theory is that of Newton,²² who has computed the edge T_e for an elongated, sharp-boundary FRC in the limit where ohmic dissipation in the sheath is balanced by classical electron thermal conduction along open field lines to the end walls; furthermore, perpendicular particle flow across the sheath is balanced against parallel free-streaming ion losses. The resulting electron temperature is independent of the particular resistivity model and is given by the equation

$$T_e \approx 5 \times B^{2/3} L^{1/3} \quad , \quad (10)$$

where T_e is in eV, the magnetic field B is in kG, and the coil length L is in cm. The model assumes collisional electrons on open field lines, which is reasonable for *LSM* since λ_{ee}/L in the sheath is typically between 0.05 and 0.1. Substituting the experimental parameters into Eq. 10, the Newton temperature ranges from approximately 86 eV for low-field conditions to 103 eV at high field. These values are consistently $1/3$ lower than the experimental values inferred at $r = r_s$; however, excellent agreement is obtained between the Newton temperature and that measured in the open-field configurations.

The second theory has been published by Correll,²³ who computed a limiting electron temperature for the situation where the power from classical equilibration between hot ions and cold electrons is balanced by electron thermal conduction and convection along open magnetic fields. In the collisional limit where conduction dominates, the limiting temperature is given by an equation which has a form remarkably similar to Eq. 10,

$$T_e = 0.22 \times [\beta_i B^2 L^2 / \lambda_{ee}]^{1/3} \quad , \quad (11)$$

where $\beta_i = \beta T_i / (T_e + T_i)$ and the units are eV, kG, and cm. Using average sheath plasma parameters, $n \approx \langle n \rangle / 2$ and $T_e \approx T_e(r_s) / 2$, Equation 11 predicts temperatures ranging from 85 eV for the low-field, low-bias 2 and 3 mtorr cases to about 105 eV for both 4 mtorr and high-field 3 mtorr. For FRC parameters inside the separatrix, Eq. 11 predicts temperatures which are 20 to 30% lower than those computed for the sheath.

An important experimental observation is the dependence of T_e on the plasma radius R . As mentioned above, T_e increases almost proportional with R ; moreover, for virtually identical n , B and L the larger *LSM* plasmas are 35% hotter than on *FRX-C*. This scaling with radius is inconsistent with both the Newton and Correll theories. We conclude that the two theories are useful in estimating an average temperature of the open-field-line sheath outside the separatrix, since they consistently predict temperatures 60 to 80% of the experimental value at $r = r_s$; however, these predictions are only lower bounds for the FRC core temperatures for the limit of no closed-field-line confinement. According to the theories, the electron temperature should increase in higher-field experiments. For example, for the *LSM Compressor*³ where $B \approx 20$ kG and $L \approx 350$ cm, Eqs. 10 and 11 both predict a minimum electron temperature of about 275 eV. If confinement in the closed-field region continues to be better than on open lines, the average sheath temperature will remain at 50-70% of the FRC core; therefore, record $T_e(R)$ values of 400 to 550 eV could be likely.

C. Flux Confinement

The characteristic decay time of the poloidal magnetic flux, $\tau_\phi = -\phi_p / (d\phi_p/dt)$, can be written as a combination of Faraday's and Ohm's laws at the field null, which for the rigid-rotor equilibrium profile is⁵

$$\tau_\phi = 7.4 \times 10^{-8} r_s^2 / \eta(R) \quad , \quad (12)$$

where $\eta(R)$ is the resistivity at the field null and all units are in mks. For each discharge, τ_ϕ is inferred from the decay of the excluded flux, thereby allowing one to estimate $\eta(R)$ from Eq. 12.

Traditionally, the inferred field-null resistivity has been compared to the classical, cross-field Spitzer value $\eta_{\perp c}$, even though $\eta(R)$ is always found to be anomalous

and the classical scaling is never observed. With $Z_{\text{eff}}=1$ and $\ln\Lambda_{\text{el}}=12$, the classical resistivity is given by¹⁶

$$\eta_{\perp c} = 1.2 \times 10^{-3} / T_e^{3/2} \quad , \quad (13)$$

$\Omega\text{-m}$, where T_e is in eV. Using the electron temperatures measured near the field null, we have computed $\eta_{\perp c}(R)$ with Eq. 13 for each discharge; subsequently, the classical flux confinement time $\tau_{\phi c}$ is determined with Eq. 12, and compared to the actual τ_{ϕ} inferred from excluded flux. The inferred resistivity anomaly factor, $\eta(R)/\eta_{\perp c}(R) \approx \tau_{\phi c}/\tau_{\phi}$, is always greater than 8, and can be as large as 150 under certain conditions. Data from the 3-mtorr, bias-field scan (see Table III and Figs. 7-12) offer an excellent opportunity to compare τ_{ϕ} with classical losses, since the classical scaling factor, $r_s^2 T_e^{3/2}$, varies by almost an order of magnitude. As illustrated by the data in Fig. 15a, there is no clear correlation between τ_{ϕ} and $\tau_{\phi c}$, indicative of a resistivity anomaly factor that increases from about 10 at low bias to 100 at high bias. Ignoring equilibrium changes (see below), one must conclude that the field-null resistivity or flux-loss anomaly on *LSM* is higher than on *FRX-C* where anomaly factors between 3 and 7 were reported.^{4,5}

The inferred flux loss remains poorly understood at present. This fact is compounded by recent 2-D MHD equilibrium computations⁷ which indicate that the τ_{ϕ} inferred in experiments could be subject to sizable errors. These errors result from variations in the current density at the field null that could go undetected by the usual excluded flux diagnostic. Unfortunately, there is no good way at present to estimate the magnitude of possible equilibrium changes.

A new theory,⁹ based on turbulence from low-frequency-drift (LFD) instabilities, has been recently developed to explain observed flux and particle loss in an FRC. A "crude" estimate of the flux confinement time from LFD activity has been derived,

$$\tau_{\phi} \approx 3 \times 10^{-8} B r_s^2 / T_e [1 + T_e/T_i]^{1/2} \quad , \quad (14)$$

where τ_{ϕ} is given in seconds, B in gauss, temperature in eV, and r_s in cm. The particle confinement time τ_N is given by the same equation. The flux confinement data from the 3-mtorr bias scan have been compared to the theoretical values predicted from Eq. 14. Results are plotted in Fig. 15b. While there is rough

agreement between the magnitudes, there appears no clear correlation with the LFD scaling factor which could be varied by over a factor of two in the experiment. One reaches a similar conclusion after comparing experimental τ_N values with the those computed from Eq. 14 (see Fig. 16).

D. 1½-D Simulation

The observed decay of the equilibrium FRC has been modeled with the Los Alamos 1½-dimensional fluid transport code *CFRX*. Details about the code may be found elsewhere.^{24,25} In brief, *CFRX* computes the time evolution of the magnetic field, plasma density, electron and ion temperature profiles as a function of the magnetic flux ψ . The radial equilibrium and transport equations (*i.e.*, the usual 1-D transport problem) are solved at each time step, subject to four additional constraints imposed by 2-D equilibria: (1) flux-surface averaging within the separatrix; (2) axial contraction (or expansion), consistent with the equilibrium constraints; (3) the average-beta condition, $\langle \beta \rangle = 1 - \frac{1}{2}x_s^2$; and (4) parallel conduction and convection between the open-field-line sheath plasma and the end walls. In the code, the resistivity $\eta_{\perp}$ is modeled as a combination of the Spitzer and Bohm values with ψ -dependent coefficients. The thermal conductivities $\kappa_{\perp}$ and $\kappa_{\parallel}$ for the electrons and ions are handled in a more limited manner with classical values modified by constant multipliers. These constants, however, may be different in the closed and open field regions. Particle confinement on the open field lines is taken to be the product of the ion free-streaming time, $\tau_{\parallel} = L/v_i$, and a constant multiplier.

A comprehensive set of simulations for all experimental conditions is beyond the intentions of this report. Instead, we have chosen to exhibit results from a single run that simulates the "best" conditions on *LSM*, low-field 3 mtorr with low bias, where the confinement is optimized and most reproducible (see Tables I and II). Initial profiles (see Fig. 17) are chosen to be consistent with the measured parameters just after formation. The ion temperature is chosen to be flat, in view of the fast rates for classical cross-field thermal conduction anticipated for an FRC with $s < 2$. The transport coefficients, $\eta_{\perp}$, $\kappa_{\perp e}$ and $\kappa_{\parallel e}$, have been varied from their classical values to obtain agreement with the measured parameters at the end of the stable period which is typically 70 μs after formation. The profiles at the end of the run are plotted in Fig. 18. As illustrated in Figs. 17 and 18, the resistivity profile is somewhat peaked inside, varying between $11\times$ classical at the separatrix and $22\times$ classical at the field

null. To maintain a relatively flat $T_e(r)$ profile that is constant in time, the electron thermal conductivities have been adjusted so that $\kappa_{\perp e} = 35 \times$ classical inside the separatrix and $\kappa_{\parallel e} = 0.18 \times$ classical outside. The anomaly factor for $\kappa_{\perp e}$ is 35% lower than that obtained in Section IV.B with simple dimensional analysis. Improved confinement on open field lines is evident by the superclassical $\kappa_{\parallel e}$. Furthermore, as found in earlier simulations of *FRX-C* data,²⁴ the particle confinement time on open field lines is $3\tau_{\parallel}$. The average global confinement times predicted by the code, $\tau_{\phi} = 160 \mu\text{s}$, $\tau_N = 180 \mu\text{s}$, and $\tau_E = 74 \mu\text{s}$, are all consistent with the experimental values inferred with the 0-D model (cf. Table I).

The *LSM* simulation is now compared to the one performed for *FRX-C* using the same 1½-D code.²⁴ For 5-mtorr conditions on *FRX-C*, the thermal conductivity anomaly factor, $\kappa_{\perp e} = 36 \times$ classical, was virtually identical to that inferred for 3-mtorr *LSM*. This finding is somewhat confusing, since the higher T_e measured on *LSM* appears to indicate improved confinement. This inconsistency may be resolved by reexamining the *FRX-C* simulation. In particular, the use of classical parallel electron thermal conductivity on the open field lines cools edge electrons too much, resulting in a low separatrix electron temperature, $T_e(r_s)/T_e(R) = 0.6$ (see Fig. 5 of Ref. 24). The temperature gradient in the simulation was significantly larger than that measured on *FRX-C*,¹ where $T_e(r_s)/T_e(R) = 0.86$ (see Fig. 4 of Ref. 1). In the simulation, the large T_e gradient, caused by large losses on the open field lines, implies a smaller $\kappa_{\perp e}$ in the closed-field-line region (cf. Eq. 7). From simple dimensional arguments, one can conclude that the classical anomaly factor $\kappa_{\perp e}$ inferred for *FRX-C* 5-mtorr conditions in Reference 24 is about three times too low, while the $\kappa_{\parallel e}$ is too high.

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TABLES

TABLE I
PRESSURE SCAN DATA

<u>PARAMETER</u>	<u>UNITS</u>	<u>2 mtorr</u>	<u>3 mtorr</u>	<u>4 mtorr</u>	<u>5 mtorr</u>
fill pressure	mtorr	2.09 ± 0.06	3.04 ± 0.05	4.05 ± 0.06	4.98 ± 0.04
bias field	mT	58 ± 3	63 ± 4	57 ± 4	71 ± 3
PI timing	μs	19.2 ± 0.1	18.6 ± 0.1	13.9 ± 0.2	13.9 ± 0.1
cusp flux	mWb	18.8 ± 0.1	18.8 ± 0.3	18.8 ± 0.1	18.8 ± 0.1
B_w	T	0.44 ± 0.01	0.41 ± 0.02	0.45 ± 0.01	0.40 ± 0.01
r_s	mm	160 ± 5	151 ± 12	167 ± 5	156 ± 15
V_s	liter	87 ± 6	104 ± 13	115 ± 7	118 ± 16
ϕ_p	mWb	4.2 ± 0.4	3.4 ± 0.8	5.0 ± 0.4	3.7 ± 1.1
$\langle n \rangle$	10^{20}m^{-3}	6.4 ± 0.4	7.4 ± 0.6	10.5 ± 0.8	11.1 ± 1.1
$T_e + T_i$	eV	670 ± 40	516 ± 34	431 ± 27	328 ± 27
τ_ϕ	μs	128 ± 53	158 ± 36	117 ± 31	25 ± 5
τ_E	μs	54 ± 11	78 ± 15	77 ± 13	23 ± 5
τ_N	μs	149 ± 101	173 ± 50	160 ± 79	40 ± 15

TABLE II
TEMPERATURE vs FILL PRESSURE

<u>PARAMETER</u>	<u>UNITS</u>	<u>2 mtorr</u>	<u>3 mtorr</u>	<u>4 mtorr</u>	<u>5 mtorr</u>
$T_e(r \approx R)$	eV	165 ± 15	156 ± 28	140 ± 14	142 ± 15
$T_e(r=0)$	eV	133 ± 24	135 ± 26	128 ± 20	117 ± 18
$T_i(r \approx R)$	eV	525 ± 44	368 ± 37	298 ± 33	204 ± 47

TABLE III
BIAS SCAN DATA

<u>PARAMETER</u>	<u>UNITS</u>	<u>low bias</u>	<u>medium bias</u>	<u>high bias</u>
bias field	mT	44 ± 5	65 ± 3	86 ± 2
fill pressure	mtorr	2.99 ± 0.01	3.04 ± 0.05	3.03 ± 0.03
PI timing	μs	18.5 ± 0.1	18.6 ± 0.1	18.7 ± 0.1
cuspl flux	mWb	18.9 ± 0.1	18.8 ± 0.1	18.8 ± 0.0
B_w	T	0.39 ± 0.01	0.41 ± 0.02	0.41 ± 0.01
r_s	mm	111 ± 9	154 ± 9	186 ± 6
V_s	liter	59 ± 9	107 ± 10	143 ± 8
ϕ_p	mWb	1.1 ± 0.4	3.5 ± 0.7	6.3 ± 0.8
$\langle n \rangle$	10^{20}m^{-3}	8.3 ± 0.6	7.2 ± 0.6	6.0 ± 0.5
$T_e + T_i$	eV	443 ± 28	521 ± 31	582 ± 34
τ_ϕ	μs	131 ± 72	160 ± 34	122 ± 48
τ_E	μs	41 ± 10	82 ± 14	69 ± 17
τ_N	μs	105 ± 24	185 ± 53	181 ± 107

TABLE IV
EQUILIBRIUM FIELD SCAN DATA

<u>PARAMETER</u>	<u>UNITS</u>	<u>low field</u>	<u>high field</u>
$B_w @ 30\mu s$	T	0.41 ± 0.02	0.57 ± 0.04
bias field	mT	65 ± 3	65 ± 3
fil pressure	mtorr	3.04 ± 0.05	3.05 ± 0.05
PI timing	μs	18.6 ± 0.1	18.6 ± 0.1
cusp flux	mWb	18.8 ± 0.1	20.4 ± 1.2
r_s	mm	154 ± 9	130 ± 8
V_s	liter	107 ± 11	69 ± 8
ϕ_p	mWb	3.5 ± 0.7	2.8 ± 0.5
$\langle n \rangle$	$10^{20} m^{-3}$	7.2 ± 0.6	10.6 ± 0.9
$T_e + T_i$	eV	521 ± 31	704 ± 55
τ_ϕ	μs	160 ± 34	122 ± 40
τ_E	μs	82 ± 14	57 ± 7
τ_N	μs	185 ± 53	122 ± 24

TABLE V**TEMPERATURE vs EQUILIBRIUM FIELD**

<u>PARAMETER</u>	<u>UNITS</u>	<u>low field</u>	<u>high field</u>
$T_e (r \approx R)$	eV	$155 \pm 27^{(a)}$	$170 \pm 30^{(c)}$
$T_e (r=0)$	eV	$135 \pm 25^{(b)}$	$155 \pm 32^{(d)}$
$T_i (r \approx R)$	eV	$368 \pm 37^{(a)}$	$505 \pm 60^{(c)}$

$^{(a)} B_w(t=30 \mu s) = 0.40 \pm 0.01 \text{ T}$

$^{(b)} B_w(t=30 \mu s) = 0.41 \pm 0.01 \text{ T}$

$^{(c)} B_w(t=30 \mu s) = 0.54 \pm 0.02 \text{ T}$

$^{(d)} B_w(t=30 \mu s) = 0.58 \pm 0.03 \text{ T}$

TABLE VI
INPUT POWER TO ELECTRONS

P_0	B_b	B_w	Equilibration	Compression	Ohmic	Total
<u>mtorr</u>	<u>mT</u>	<u>T</u>	<u>eV/μs</u>	<u>eV/μs</u>	<u>eV/μs</u>	<u>eV/μs</u>
2	58	0.44	2.3 ± 0.5	0.6 ± 0.1	0.3 ± 0.1	3.2 ± 0.5
3	53	0.41	1.7 ± 0.8	0.3 ± 0.1	0.2 ± 0.1	2.2 ± 0.7
3	86	0.41	1.2 ± 0.8	0.5 ± 0.1	0.5 ± 0.1	2.2 ± 0.8
3	65	0.54	3.4 ± 1.8	0.9 ± 0.1	0.3 ± 0.0	4.6 ± 1.9
4	57	0.45	2.0 ± 0.7	0.3 ± 0.0	0.3 ± 0.1	2.6 ± 0.7
5	71	0.40	0.8 ± 0.7	2.0 ± 0.5	1.0 ± 0.2	3.9 ± 0.8
5	92	0.40	1.9 ± 0.6	1.3 ± 0.2	1.0 ± 0.3	4.2 ± 0.9

TABLE VII
ELECTRON POWER FLOW

P_o	B_b	B_w	P_{in}	P_{Ne}	P_{Ee}	P_{Ee}/P_{tot}
<u>mtorr</u>	<u>mT</u>	<u>T</u>	<u>MW</u>	<u>MW</u>	<u>MW</u>	<u>%</u>
2	58	0.44	43 ± 8	26 ± 12	32 ± 8	21 ± 6
3	53	0.41	40 ± 13	28 ± 7	28 ± 16	26 ± 16
3	65	0.54	80 ± 35	42 ± 9	63 ± 36	29 ± 12
4	57	0.45	75 ± 17	48 ± 18	56 ± 22	38 ± 16

TABLE VIII
ROUGH ESTIMATES OF TRANSPORT COEFFICIENTS

P_o	B_b	B_w	$\chi_{\perp}$	$\kappa_{\perp}$	$\kappa_{\perp c}$	$\kappa_{ c}$
<u>mtorr</u>	<u>mT</u>	<u>T</u>	<u>$m^2 s^{-1}$</u>	<u>$m^{-1} s^{-1}$</u>	<u>$m^{-1} s^{-1}$</u>	<u>$m^{-1} s^{-1}$</u>
2	58	0.44	250	1.6×10^{23}	2.2×10^{21}	4.4×10^{27}
3	53	0.41	285	2.1×10^{23}	3.9×10^{21}	4.2×10^{27}
3	65	0.54	557	5.9×10^{23}	5.4×10^{21}	5.5×10^{27}
4	57	0.45	714	7.5×10^{23}	5.4×10^{21}	3.5×10^{27}

FIGURES

Fig. 1: Schematic diagram of the single-point Thomson scattering electron temperature diagnostic used on *FRX-C/LSM*.

+FRXC shot 10651 31-Oct-88 1100 mode 0 type 0 26880
 Bank-kV MB 44.6 CB 70.9 BB 5.3 PI 44.6 CU 4.0 QB 0.6 CV 0.2 CI 0.0
 P-torr TP 3.09
 Time-us

Fig. 2: Thomson scattering data obtained from a single discharge on FRX-C/LSM.

Fig. 3: FRC electron temperature data obtained from *LSM* at 2 mtorr, low bias, and low external field.

Fig. 4: FRC electron temperature data obtained from *LSM* at 3 mtorr, low bias, and low external field.

Fig. 5: FRC electron temperature data obtained from *LSM* at 4 mtorr, low bias, and low external field.

Fig. 6: FRC electron temperature data obtained from *LSM* at 5 mtorr, low bias, and low external field.

Fig. 7: Poloidal magnetic flux (a) measured at zero crossing and (b) inferred for the equilibrium FRC at time $t = 30 \mu s$ plotted vs the initial bias flux for LSM operations at 3 mtorr and low external field.

Fig. 8: FRC separatrix radius at $t = 30 \mu s$ vs initial bias magnetic field for LSM operations at 3 mtorr and low external field.

Fig. 9: FRC separatrix volume, average density, pressure balance temperature, and particle inventory at $t = 30 \mu\text{s}$ vs separatrix radius measured in LSM during the 3-mtorr bias scan.

Fig. 10: Electron temperatures at $t = 30 \mu s$ vs FRC separatrix radii measured in LSM during the 3-mtorr bias scan. Each data point is from a separate discharge.

Fig. 11: Electron temperatures at $t = 30 \mu s$ vs FRC separatrix radii measured in LSM during the 3-mtorr bias scan. Data from Fig. 10 are averaged into five points with error bars denoting the standard deviations.

Fig. 12: Inferred field-null ion temperatures at $t = 30 \mu\text{s}$ vs FRC separatrix radii obtained in *LSM* during the 3-mtorr bias scan. Individual data points are plotted in top graph while averages of same data are shown at bottom.

Fig. 13: FRC electron temperature data obtained from *LSM* at 3 mtorr, low bias, and high external field.

+FRXC shot 10867 14-Nov-88 1134 mode 0 type 0 26880
 Bank-kV MB 45.0 CB 70.8 BB 5.8 PI 44.4 CU 4.5 CU 0.2 CI 0.0
 P-mtorr TP 3.10
 Time-us

Fig. 14: Representative data obtained from Thomson scattering at the geometric axis on *LSM* at 3 mtorr, low bias, and high external field. Poor single-temperature fits were consistently observed only for this situation.

Fig. 15: Experimental flux confinement times plotted vs theoretical predictions from (a) classical and (b) low-frequency-drift instability theory.

Fig. 16: Experimental particle confinement times plotted against the theoretical predictions from low-frequency-drift instability theory.

Fig. 17: Initial profiles used in the 1-D simulation of an average low-bias, low-field, 3-mtorr LSM discharge.

Fig. 18: Final profiles computed at $t = 70 \mu\text{s}$ from the 1%-D simulation of an average low-bias, low-field, 3-mtorr LSM discharge.