A High-Density Field Reversed Configuration Plasma for Magnetized Target Fusion

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***Abstract*—We describe a program to demonstrate the scientific basis of magnetized target fusion (MTF). MTF is a potentially low-cost path to fusion which is intermediate in plasma regime between magnetic (MFE) and inertial fusion energy (IFE). MTF involves the compression of a magnetized target plasma and pressure times volume (PdV) heating to fusion relevant conditions inside a converging flux conserving boundary. We have chosen to demonstrate MTF by using a field-reversed configuration (FRC) as our magnetized target plasma and an imploding metal liner for compression. These choices take advantage of significant past scientific and technical accomplishments in MFE and defense programs research and should yield substantial plasma performance ($n\tau > 10^{13}$ s-cm^{-3} $T > 5$ keV) using an available pulsed-power implosion facility at modest cost. We have recently shown the density, temperature, and lifetime of this FRC to be within a factor of 2–3 of that required for use as a suitable target plasma for MTF compression for a fusion demonstration.**

***Index Terms*—Field-reversed configuration, fusion energy, magnetized target fusion (MTF).**

I. Introduction

We DESCRIBE a primarily experimental program to demonstrate the scientific basis of magnetized target fusion (MTF). MTF could be a reduced-cost path to a more attractive fusion energy system that takes advantage of a plasma regime between magnetic (MFE) and inertial fusion energy (IFE). Adiabatic compression of a magnetized target plasma would yield PdV heating to fusion relevant conditions inside a converging flux conserving boundary. We are exploring an innovative approach for creating compact pulsed plasmas with high β and high temperatures.

Our proposed physics demonstration of MTF requires a field-reversed configuration (FRC) magnetized target plasma and its translation into a region where an imploding metal shell can compress the plasma. A schematic is shown in Fig. 1. This strategy takes advantage of significant past scientific and technical accomplishments in MFE and defense programs research and should yield substantial plasma performance ($n\tau > 10^{13}$ s-cm^{-3} $T > 5$ keV) using an available pulsed-power implosion facility at very modest cost.

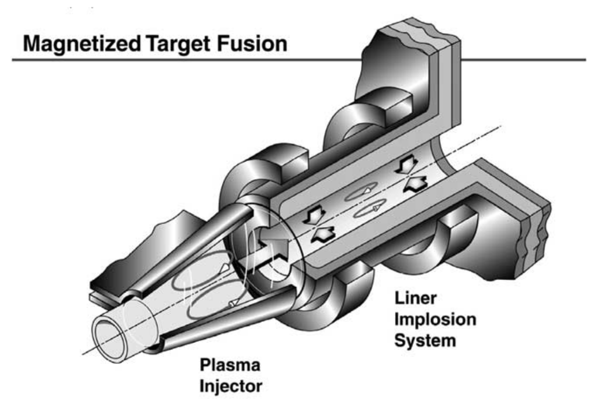

Fig. 1. MTF schematic showing plasma formation region and liner implosion section.

This FRC has high-plasma density, n near 10^{17} cm^{-3} before compression and is expected to have $n > 10^{19}$ cm^{-3} after compression. As plasma equilibrium it has high power density and $\beta \approx 1$, where β is the ratio of plasma particle pressure to external confining magnetic field. There is a large confining magnetic field, 5 T prior to compression, and 500 T after compression. The auxiliary heating power level from the theta-pinch formation is on the order of 100 MW, and approximately 1000 GW during flux conserver compression.

Among alternate fusion concepts, the choice of the FRC configuration for MTF also confers the following other advantages:

1) small size which results in reduced total construction cost; the heart of the device sits on a table top;
2) geometric simplicity, because no captured magnetic coils or center stack ohmic transformer are required;
3) magnetic simplicity, because no toroidal magnetic field, or linked magnets are required;
4) heat exhaust handling includes a natural axial divertor;
5) advanced fuel potential could be realized at high β and large ion temperature;
6) in a reactor, each pulse would utilize a fresh liquid first wall;
7) repetition rate of 0.1 Hz, so that there would be time to clear the reactor chamber after each power pulse event;
8) most of the initial physics research can be conducted with existing facilities and technology.

We are not far from what is needed for a suitable target plasma for MTF compression and a fusion energy demonstra-

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tion experiment. We show the high density and temperature of this FRC to be within a factor of 2–3 of that required, and found the lifetime to be within 2/3 of the design goal. This integrated project benefits from multiple collaborations with the Los Alamos National Laboratory (LANL), Air Force Research Laboratory-Kirtland (AFRL), Lawrence Livermore National Laboratory (LLNL), and General Atomics (GA).

II. Background: Science and Technology

A. MTF

MTF is a subset of magneto-inertial fusion (MIF), which includes all pulsed, high-pressure approaches to fusion involving inertial confinement of a plasma that require magnetic field in an essential way. For example MIF concepts include laser-heated solenoid plasmas, cryogenic fiber Z-pinches, flow-stabilized stabilized Z-pinches, and the composite Z-θ pinch. MTF specifically requires an imploding pusher to compress and PdV (where pressure P acts on a differential volume change dV) heat a magnetized target plasma, such as a spheromak or FRC, to fusion conditions. MTF involves plasma regimes intermediate ($n \sim 10^{19} - 10^{20}$ cm^{-3} and $T \sim 5$ keV) between MFE and IFE and seeks to capitalize on the advantages of this intermediate regime (described in the following) [1]–[3]. Various flux conserving materials have been considered for the imploding pusher, including metal liners, gaseous or plasma pushers [4], and compressible liquid shells [5], [6].

B. Motivation: A Potential Low Cost Route to Fusion

Density is one of the few adjustable free parameters in the design of a fusion system, particularly when seeking a lower cost development path [2]. The fusion energy production per unit volume scales as density squared

$$P_{\text{fusion}} \approx n^2 \langle \sigma v \rangle E_f \tag{1}$$

where n is the density [m^{-3}], $\langle \sigma v \rangle$ is the fusion reaction rate [m^3 s^{-1}], and E_f is the energy per fusion reaction. The losses per unit volume can be characterized with a loss time τ_E so that

$$P_{\text{loss}} \approx \frac{nT}{\tau_E} \tag{2}$$

where T is the characteristic ion temperature. The ratio of $P_{\text{fusion}}/P_{\text{loss}}$ is Q, which depends only upon the temperature and the well known Lawson product

$$Q \approx n\tau_E \langle \sigma v \rangle \left(\frac{E_f}{T} \right). \tag{3}$$

If we assume the systems have size r and diffusive losses χ (probably anomalous) then the energy confinement time can be defined

$$\tau_E = \frac{r^2}{\chi}. \tag{4}$$

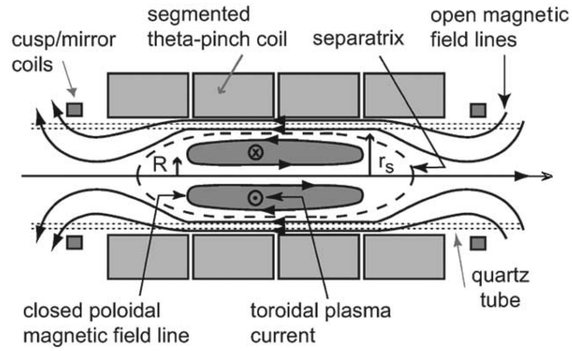

Fig. 2. FRC schematic of cylinder geometry including poloidal magnetic fields, toroidal current, theta-pinch coil, cusp/mirror coils, closed and open magnetic surfaces.

Since system cost and size scale approximately with the plasma energy E_{p}, we can roughly estimate the cost as

$$E_{\text{p}} \approx nTR^3 \approx \left(\frac{\chi^{\frac{3}{2}}}{n^{\frac{1}{2}}} \right) \left(\frac{T^{\frac{5}{3}} Q}{\langle \sigma v \rangle E_f} \right)^{\frac{3}{2}}. \tag{5}$$

For a D–T fusion scenario, the right-hand term on the right-hand side is relatively constant because $T \approx 10$ keV, $Q > 1$, $\langle \sigma v \rangle E_f$ is fixed. Thermal diffusivity χ is important, but relatively difficult to improve. Only density remains as the variable that we can use to influence the energy of a fusion system. Compared with MFE research, the necessity of reducing thermal diffusivity is relaxed because MTF operates at much higher densities than the MFE approach. Using conventional magnet technology and the engineering of steady-state power handling, the "conventional MFE density" typically is in the range of 10^{14} cm^{-3}. Inertial fusion scenarios are conceived as working with pulsed systems at much higher density and no magnetic field. On the other hand, a pulsed approach like MTF that takes advantage of magnetic thermal insulation could have much larger density than MFE and smaller χ than ICF.

C. FRC as a Target Plasma

MTF invokes the compression of a magnetized target plasma to fusion conditions. Compact toroids such as the spheromak and FRC have been identified as candidate target plasmas candidates for MTF because of several potentially favorable features: 1) closed field line topology; 2) lack of internal material objects facilitating compression within a liner; and 3) ability to be translated from the plasma formation region into a liner for compression. LANL has a long history of toroidal confinement experiments, including the reversed-field pinch (RFP), spheromak, and FRC. We have chosen the FRC as the candidate that can best survive formation, translation, and compression [7], [8], [38], and which also offers some unique advantages over other possible targets.

The FRC is an elongated, self-organized compact toroid state that has toroidal plasma current and poloidal magnetic field. In Fig. 2 we indicate the FRC as a closed-field-line torus inside a separatrix radius r_s with an open-field-line sheath outside the separatrix. FRC equilibrium balances plasma pressure with radial magnetic field pressure and axial field-line "tension." For an ideal straight cylinder it has been shown [9], [10] that volume averaged pressure inside the separatrix $P = nT = n(T_e + T_i)$, normalized to the external magnetic field pressure, is

$$\langle\beta\rangle = 1 - \frac{x_s^2}{2} \tag{6}$$

where

$$x_s = \frac{r_s}{r_c} \tag{7}$$

and r_c is the coil radius, $\beta = nT/({B_{\rm ext}}^2/2\mu_0)$, $B_{\rm ext}$ is the external separatrix magnetic field, n is the density and T is the temperature. The FRC has high plasma beta $\langle\beta\rangle \sim 1$, evaluated with respect to $B_{\rm ext}$. Active worldwide FRC research has resulted in significant experimental and theoretical progress, resulting in stable plasmas with good confinement properties.

The FRC offers many potential advantages as an MTF target plasma, including the promise of robust, closed flux surfaces that maintain their topology during compression, as has been observed [11] in compression, translation [12], stability experiments [13], and models [14]. Formation of an FRC using high-voltage theta-pinch technology is well established, and the plasma characteristics of the FRC (i.e., stability, transport, and impurity content) in the density and temperature range of interest are reasonably well characterized. Early reversed-field theta pinches formed FRC's exceeding our target density [15]–[18], but the diagnostic methods and theoretical understanding were less complete in the 1960s–1970s. The following are other desirable features.

1) The FRC has been shown to exhibit resiliency during translation and deformation.
2) Because of field line tension, the FRC undergoes axial contraction during radial compression [19]. A cylindrical adiabatic implosion (r_c contracts) obeying (6) and conserving particles yields an FRC volume that scales as ${r_c}^{2.4}$, i.e., more strongly than a two-dimensional (2-D) compression given by ${r_c}^2$ [20]. A full three-dimensional (3-D) compression could be achieved with shaped liners.
3) FRCs are formed inductively and are largely free of impurity line radiation.
4) The open field lines outside the separatrix act as a natural divertor that isolates plasma loss flux from wall boundaries.

The latter two attributes may substantially reduce impurity mixing, a concern for MTF.

D. Theta-Pinch Formation

For MTF, the FRC plasma must survive long enough to translate into the liner volume for implosion. Fusion energy breakeven $Q = 1$ at expected implosion convergence factors requires sufficient plasma pressure. The key physics governing both lifetime and pressure is determined by magnetic flux retention during the FRC formation process. Theta-pinch FRC formation [8] uses an initial bias magnetic field (0.3–0.5 T for field reversed configuration experiment-liner (FRX-L) that is frozen in during preionization (PI), and then radially shocked by another reversed main bank field that is much larger (3–5 T in FRX-L). The radial jump in magnetic field induces a plasma toroidal image current. Field line reconnection at the ends then forms closed flux surfaces. Formation (2–3 μs) and translation ($v_A \sim 10$ cm/μs) into the liner region can be accomplished [12] in a few μs, a time short compared to the expected FRC lifetime (20–25 μs). Two-dimensional magnetohydrodynamic (MHD) simulations [14] suggest that FRC compression could be underway 5 μs after implosion.

Our theta-pinch formation method takes advantage of a large ($E_\theta \approx 1$ kV/cm) azimuthal electric field which increases the radial $E_\theta \times B_z$ implosion velocity and consequently the Green–Newton [11], [21], [22] magnetic field. This field corresponds to equal Alfvén and $E \times B$ drift speeds at the edge

$$v_A = \frac{E_\theta}{B_{\rm GN}} \tag{8}$$

so that

$$B_{\rm GN} = E_\theta^{\frac{1}{2}}(\mu_0 nm)^{\frac{1}{4}}. \tag{9}$$

In practical units

$$B_{\rm GN} = 1.88\ E_\theta({\rm kV/cm})^{1/2}\ (A_i {\rm p}_0({\rm mtorr}))^{1/4}$$

where A_i is the ion mass in proton units, and for FRX-L operation at $\mathrm{p}_0 \approx 40$–80 mT, $B_{\rm GN} \approx 0.5$–0.7 T. A high $B_{\rm GN}$ is desirable because $B_{\rm GN}$ limits the maximum trapped flux and, hence, the maximum plasma pressure in a theta pinch formed FRC. Increasing magnetic liftoff field $B_{\rm LO}$ that is trapped (when the main field reverses and the FRC "lifts off" the wall) relative to $B_{\rm GN}$ can also increment resistive flux dissipation heating over the usual radial shock heating. The desired initial temperature ($T_i \approx T_e \approx 250$ eV) and trapped flux correspond to a bias field $B_{\rm bias} = 0.3 - 0.7$ T. There is experimental evidence [23], [24] that a pressure bearing sheath forms which slows the flux loss during formation from convective to diffusive. Simple estimates of the magnetic lift-off field that is trapped (when the main field reverses and the FRC "lifts off" the wall) may be unduly pessimistic for large values of $B_{\rm bias}/B_{\rm GN} > 0.5$ where we operate FRX-L. On the other hand, our collisional FRC (ion mean-free path $\lambda_i \sim 1$–2 cm compared to separatrix radius $r_s \sim 2$ cm) may have worse flux retention properties during formation than those observed at lower density.

E. Fundamental FRC Physics

Although this research is focused on achieving MTF using an FRC, it also offers a strong plasma science component. The FRC configuration is unique among magnetic configurations. Among its unique properties are

1) high plasma $\beta \sim 1$;
2) no or very little toroidal field;
3) dominant cross-field diamagnetic current and flows;
4) vanishing rotational transform, magnetic shear, and helicity;
5) stability that defies MHD predictions.

Consequently, the FRC is a valuable platform for exploring fundamental plasma physics which gives rise to these properties. One example is to understand the effect of strong flows on plasma equilibria and stability. Another is to explore the validity of generalized relaxation principles which may govern FRC formation and equilibria, such as minimum dissipation theory [25]–[27]. Some of these fundamental plasma physics questions reach beyond MHD single fluid models and may be related to geophysical and astrophysical phenomena.

F. Liner Implosion Technical Issues

The broad utility of high-energy liners in defense programs and high-energy density programs has led to significant investment in liner physics studies and technology advancement that will be useful for MTF. A flux conserving shell (liner) will be used to implode the MTF target. The interactions of the liner with the plasma interior involve physics and engineering questions that also need to be investigated in the final stages of this project, which culminate in an integrated liner-on-plasma experiment [1], [2], [28]–[30].

III. Technical Progress Overview

During the last four years, we have made major progress in creating a high-density FRC target for MTF. We also successfully imploded two aluminum liners onto vacuum at AFRL-Kirtland, demonstrating parameters appropriate for our proposed liner on plasma experiment [28]–[30].

The first three years of the past four-year project were consumed by the design, construction, testing, and integration of a high-voltage, high-current, pulsed-power experiment. By year two, we had assembled the essential FRC apparatus, including a low-inductance transmission line header that coupled the cable connections from the main capacitor bank to the single turn theta coil. Shakedown activities included finding a feasible compromise between good grounding, inductive connections, charging and firing configurations. We characterized the preionization process, and worked on suppression of electrical noise. Initially, we had no position control of the FRC that formed, and the apparent quick "loss" of the plasma indicated by midplane diagnostics was a symptom of the FRC squirting out axially. The addition of cusp/mirror coils to each end of the theta coil along with capacitor banks and control systems aided magnetic reconnection during the FRC formation and kept the FRC centered underneath the theta coil. These resulting FRC equilibria had long lifetime, allowing growth of the classic $n = 2$ rotational instability which finally terminates the FRC.

We have formed high density FRCs that are within factors of 2–3 of the desired target parameters [8] and have fielded an array of diagnostics to measure many important characteristics. At the time of the peak current for the main bank, the formation parameters are quite acceptable, but they deteriorate as the FRC main bank rings later in the shot. The decompression of the FRC is due to crowbar switch modulation of the theta coil magnetic field, which results in large flux losses, and particle and stored energy losses as the FRC expands beyond the length of the theta coil. Typical current waveforms for cusp coils, theta-coil current in Fig. 3(a) and a time expanded view of the bias, PI, and main bank with ringing crowbar modulation in Fig. 3(b). The crowbar modulation was improved during the summer of 2003.

Typical formation (and equilibrium) parameters are density $> 7 \times 10^{16}$ cm^{-3}(3×10^{16} cm^{-3}), temperature $T = T_e + T_i >$ 400 eV (200 eV), excluded flux $>$ 3 mWb (1 mWb), and internal flux $\approx$ 0.4 mWb (0.2 mWb); as will be shown later. Improved operation requires an increase in the trapped FRC equilibrium flux. The path to this end depends mostly on incremental improvements in the pulsed-power systems to increase the bias and PI fields, increases of gas prefill pressure, exploration of pre-PI schemes, and optimizing the timing sequence.

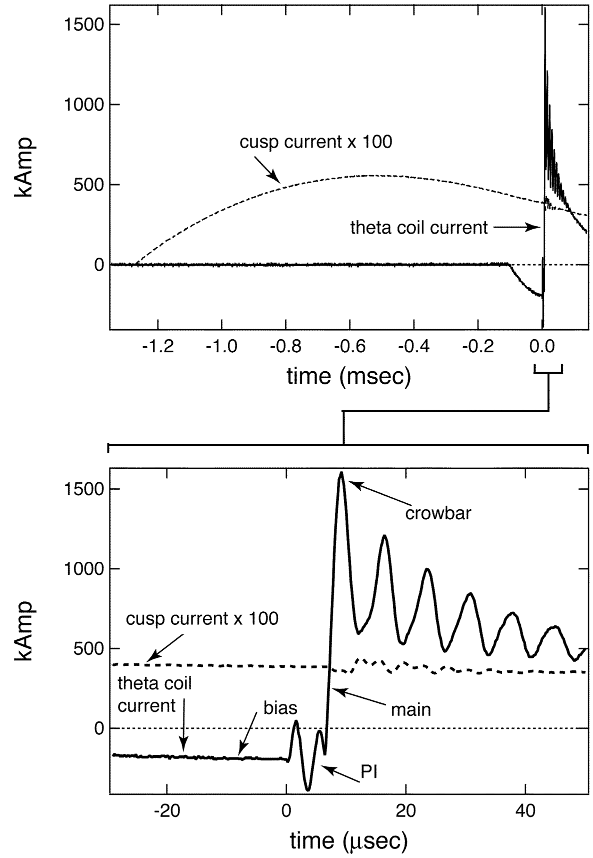

Fig. 3. Waveforms of cusp/mirror, PI, bias, and main bank currents. Cusp coils fire on the slowest time scales.

Even though high density FRCs were discovered 35 years ago, much has been forgotten about how to specifically operate in this regime. To prepare for translation and fast liner compressional heating, we require guidance from our suite of diagnostics to increase the FRC density (to $\sim 10^{17}$ cm^{-3}), temperature (to $T_e \approx T_i \approx 300$ eV) and energy confinement time (to > 10 μs). The key to all of these goals relies on increasing the magnetic flux that is trapped during formation.

A. PI and Formation

We benchmarked the PI startup plasma using only the bias and PI banks, when the main bank system was still under construction. The initial ringing theta-pinch behavior has good azimuthal symmetry until late times. As seen in Fig. 3, our chosen θ-PI technique rings the theta (θ)-pinch coil at high frequency, induces a large azimuthal E_θ field which breaks down the gas. The inductively coupled θ-PI method is very clean ($Z_{\text{eff}} \approx 1$ historically) compared to a Z-pinch axial current discharge PI approach with internal electrodes. It provides a high ($\approx$100%) level of ionization, and is more likely to work at our high fill pressure (40–80 mtorr).

Fig. 4 shows a series of images for a bias and PI shot 87, captured with an Imacon 750 fast framing camera on film, at a fill

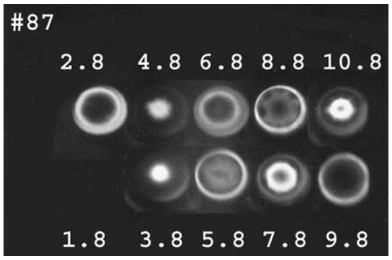

Fig. 4. Framing camera images of end-on visible emission, taken at 1-μs intervals, showing initial annular plasma breakdown, followed by radial breathing of the ringing theta pinch (PI+ bias) phase. Notice the high order flute structure developing late in time.

pressure of 43 mtorr (D_2). The zero crossings of the magnetic field due to the PI cancellation of the bias field are estimated to occur at $t = 2.6,\ 3.7,\ 6.2,\ 6.8\ \mu$s. The light emission profile can be seen to breathe radially as the confining magnetic field changes. At $t = 8.8\ \mu$s, a flute like instability can be seen.

B. Density Measurements

In Fig. 5, we show one typical shot with many FRC characteristics that can be inferred from the magnetics and density measurements. The left-hand column displays line density and density derived from the multichord interferometer. The central (solid line) and off-axis (dotted line) chords show the $n = 2$ rotational instability at $t = 16\ \mu$s that triggers the demise of many FRCs, consistent with an oval shape spinning about the z axis. For this shot, peak formation density exceeds 4×10^{16} cm^{-3} and equilibrium density is 2×10^{16} cm^{-3}. There exist other shots with larger density but lower temperature, i.e., similar plasma pressure. The separatrix shape is estimated by fitting an ellipsoidal shape to r_s data at four axial locations. Particle inventory follows from this volume times the density measured by the interferometer.

C. Improvements in Cusp Formation

The encouraging data typified by Fig. 5 followed installation of cusp/mirror coils at either end of the theta coil. A cusp configuration is created with respect to the initial bias field that evolves to a mirror 2–3 μs later with respect to the reversed main bank field. The X-point field nulls enable consistent magnetic reconnection and good FRC formation. The mirror centers the FRC under the theta coil instead of "squirting" it out axially. Next year, the translation experiment will take advantage of asymmetric mirrors to allow the FRC to exit one end and translate axially to a liner experimental region.

1) Flux Trapping: The theta-pinch approach tends to trap less than half [10] of the initial bias field. The disadvantage follows from the contradictory requirements between high peak current (i.e., large capacitance) necessary to cancel out the bias field (i.e., create zero crossings for bias), and a fast ringing frequency (i.e., small capacitance). [21], [31]–[34]. Visible light diagnostics were used initially to optimize the timing and magnetic field settings.

We had thought that our single main bank module would be marginal to attain these parameters, but our FRC pressure seems to be more constrained by how much bias flux is trapped than the main bank compression field. This FRC is slightly over compressed and has small normalized radius $x_s < 0.3$ because the trapped flux is low. Peak formation excluded flux is $\Phi_{\rm exc} \approx 3$ mWb and during decompressed equilibrium $\Phi_{\rm exc} \approx 1.5$ mWb. The internal flux estimated from the relation [11]

$$\Phi_{\rm int} \approx \pi {r_c}^2 B_{\rm ext} \left(\frac{x_s}{2^{\frac{1}{2}}}\right)^{3+\varepsilon} \tag{13}$$

is approximately 0.4 mWb at formation and 0.15 mWb during equilibrium. Here, $B_{\rm ext}$ is the measured axial magnetic field used for the excluded flux data, ϵ is a profile dependent parameter that falls between 0 (high flux sharp boundary limit) and 1 (low flux sharp boundary limit). We have chosen $\epsilon \approx 0.25$ consistent with past FRC experiments at LANL [11]. The liftoff flux $\Phi_{\rm LO}$ is taken to be the value of estimated internal flux at the liftoff time. The liftoff time $t_{\rm LO}$ is assumed to be the moment when the density from the interferometer starts to increase, e.g., in Fig. 5 density trace at $t \approx 10\ \mu$s. The equilibrium internal flux is a smaller (15%) than expected fraction (30%) of the lift off flux, compared with a scaling estimate

$$\frac{\phi_{\rm int}}{\phi_{\rm LO}} \approx 0.85\ r_{\rm wall}(m) P_0^{\frac{1}{2}}(\text{mtorr}) \tag{14}$$

which favors large radius experiments instead of FRX-L. The modulation of $B_{\rm ext}$ from the crowbar switch can also be seen at the bottom of column 2 in Fig. 5. The apparent modulation of the estimated internal flux (phi-int, bottom of right hand column) indicates that this estimate is suspect. It is physically reasonable to suppose that flux is lost, but not that it could be regained during the shot, as Fig. 5 would have us believe. Problems with the separatrix radius data lead to this and a similar apparent but suspect oscillatory behavior in temperature at time $t \approx 15\ \mu$s. Flux loss may occur when the length (2× half length, top of right hand column) of the FRC separatrix exceeds the coil length (36 cm), thus eliminating the cylindrical flux conserving radial boundary that confines the equilibrium. If the closed flux surfaces bulge out the end of the theta coil and touch the quartz tube vessel, large particle losses would ensue. It is hard to estimate a flux confinement time τ_ϕ or conclude whether it is consistent with τ_N.

D. Confinement of Particles

Using the average $\langle\beta\rangle$ condition and pressure balance yields for Fig. 5 an average temperature $\langle T_e + T_i\rangle \approx 300$ eV for formation and ≈200 eV for the equilibrium period. The apparent modulation in temperature after $t = 15.5\ \mu$s is probably not real, but follows because we divide the calculated beta by the modulated density during the $n = 2$ rotational mode. The particle e-folding confinement time $\tau_N \approx 10\ \mu$s can be estimated from the time history of particle inventory (right-hand column), inferred from interferometer density multiplied by an assumed ellipsoidal separatrix volume constrained by measured r_s data at different axial locations. The particle inventory estimate shows an average monotonic decrease after formation, in spite of the large crowbar modulated variations in $B_{\rm ex}$, which is a physically reasonable behavior. This gives confidence about our physical assumptions (elliptic shape, r_s measurement, $\text{density} = \text{line density}/2r_s$) built into this estimate.

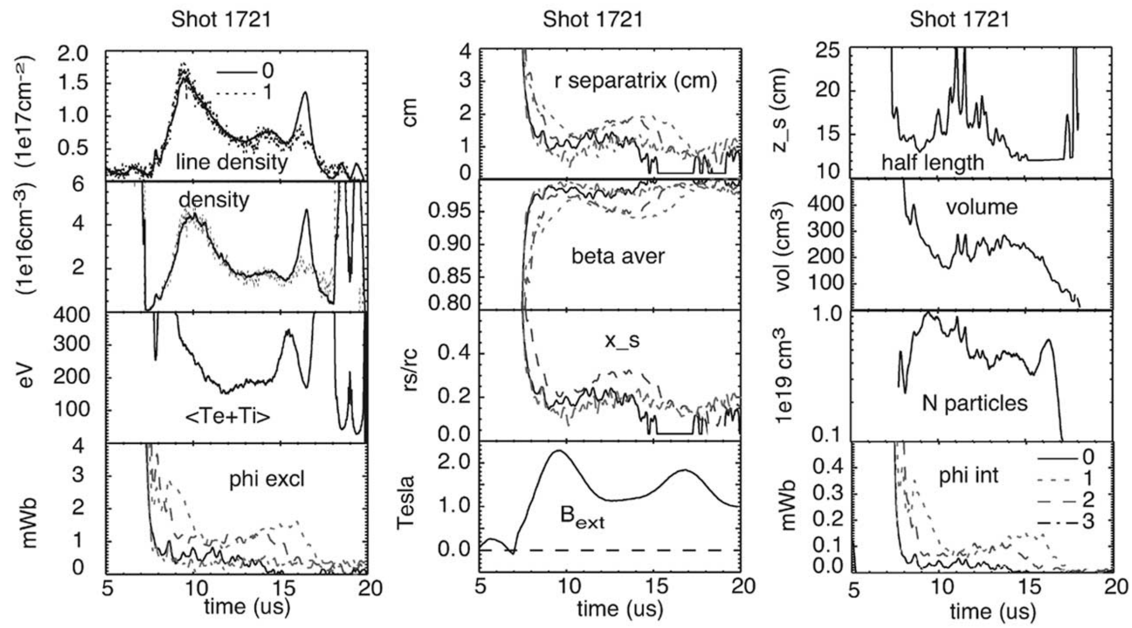

Fig. 5. Analysis of one shot showing many quantities that can be inferred from excluded flux and interferometer (0–on axis; 1–2 cm—off axis) data. For the internal flux plot (phi int) indexes 1, 2 represent flux loops that straddle the midplane axially and 0, 3 loops are closer to the ends of the theta coil.

E. Equilibrium Characteristics

Separatrix radii for four axial locations are inferred from excluded flux data. The excluded flux array together with the multichord interferometer provide essential information on FRC formation and equilibrium. The separatrix radius r_s can be inferred from axial magnetic flux loop data and a local magnetic field value B_{ext} in the region between the separatrix and the interior theta coil wall radius r_c. Using radial and axial pressure balance, (6) for volume-averaged beta $\langle\beta\rangle = 1 - {x_s}^2/2$ [9], [10] and interferometer density, we can back out the total temperature $T = T_e + T_i$ The plasma particle energy is estimated from the product of the Fig. 5 particle inventory and average energy per particle (temperature).

F. Radial Profiles of Density

Multichord interferometer data can be inverted to estimate the density profiles. Fig. 6 shows crude radial profiles, one each microsecond from formation through equilibrium and decompression. The estimated major and separatrix radii $[r_s = (2)^{1/2}\ r]$ from the excluded flux array are also indicated on the plots. During the equilibrium phase, the density profiles tend to be hollow at $r \approx 0$ and flat near $r \approx r$ as expected. Eventually, the new Thomson scattering diagnostic will provide an independent measurement of the electron temperature at six axial spatial points on each shot. This point data will be compared with the results inferred from the excluded flux data bulk temperature derived from pressure balance, excluded flux, and line density. We also will soon cluster more interferometer chords in the central and edge regions of the FRC, yielding the resistivity at the field null and separatrix [35]–[37].

G. Configuration Lifetimes

Several campaigns have been undertaken to explore the experimental knobs available to us. Surveys of fill pressure have

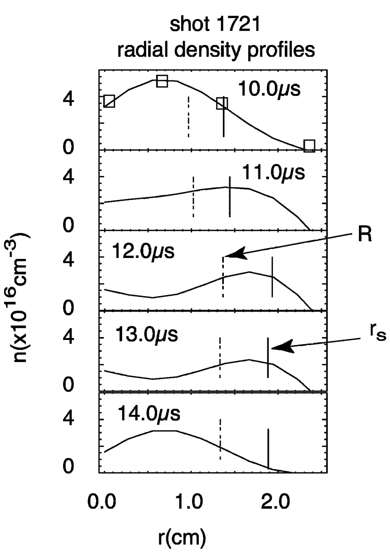

Fig. 6. Polynomial fits to multichord interferometer density data. Squares indicate chord locations.

been carried for 20 mtorr $< P_0 <$ 300 mtorr. The PI bank voltage has been pushed to 55 kV. The bias field has been increased to $\approx$ 0.3 T. From a database of 35 shots, for "typical" operation, FRC lifetimes are shown in the histogram of Fig. 7, and are mostly in the range of $\sim$ 10 μs, but extend toward 20 μs in a few cases. For these shots, we varied fill pressure from 30 to 60 mtorr, as well as the trigger timing for PI and crowbar relative to the main bank trigger. We expect this to improve as fields/fluxes are increased.

H. Survey of Typical Operating Regimes

Trigger timing is also important. As the pulsed power systems become more robust, we can operate closer to the voltage limits. Typical number of shots per week is on the order of 30, with

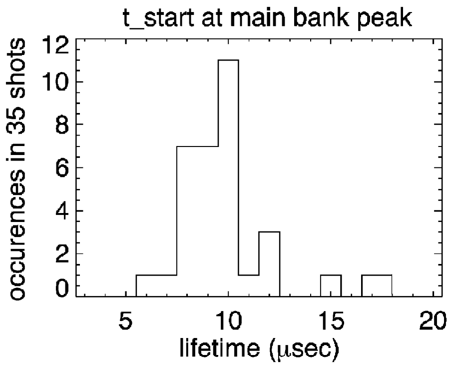

Fig. 7. Histogram summarizing 35 shots and the typical FRC lifetimes. For these shots, we varied fill pressure from 30 to 60 mtorr, as well as the trigger timing for PI and crowbar relative to the main bank trigger.

TABLE I
SUMMARY OF TYPICAL SHOT PARAMETERS FOR FRX-L DATA AS OF MAY 2003, FOR PEAK AND EQUILBRIUM VALUES. DESIGN GOAL PARAMETERS ARE LISTED IN THE LEFT-HAND COLUMN

Parameter	design spec	present FRXL	present FRXL
		Peak	**equil**
coil electric field: (kV/cm)	1	0.85	0.85
coil radius (cm)	5.0	6.2	6.2
separatrix radius (cm)	2.5	2.2	2.5
coil length (cm)	36	36.0	36.0
separatrix length (cm)	35	25.0	35.0
B external (T)	5.4	2.5	2.0
B_bias (kG)	5	3	3
B_GN (kG)	6.6	5.6	5.6
Po gas fill (mTorr)	80	40	40
peak density (10^{17} cm^{-3})	1.2	0.6	0.3-0.4
$T_e + T_i$ (keV)	0.6	0.3	0.2
plasma energy (kJ)	5.0	0.6	0.4
τ_N (μs)	28.0	-	12.0
particle inventory (10^{19})	5.0	1.0	1.0
Φ_{bias} (mWb)	4	2.8	2.8
Φ_{LO} (mWb)	4	2	2
Φ_{int} internal flux (mWb)	1.0	0.3-1.0	0.2-0.3
Ion skin depth c/ω_{pi} (cm)	0.1	0.13	0.18
S*	25	16	12
s	2.9	0.5-1.6	0.5-1.6
E	7	6.0	5.0
S*/E	3.5	2.4	2.1

approximately 30% being main bank shots. We have brought the experiment to the point where the pulsed power systems generally work and we can take 5–10 main bank shots on a good day. We would like to increase both the initial bias and PI field by approximately 50%, and trap considerably more flux in the FRC. The main bank operating voltage is at the low end of its capability, and can be increased without a problem.

Incremental pulsed power improvements along with exploration of the operating parameters in November 2002–April 2003 have resulted in ≈500 shots with ≈200 main bank shots and >60 good "typical" shots. The average shot parameters are summarized in Table I. The columns indicate from left to right, parameters for design goal, peak, and equilibrium FRCs. The measured parameters have been used to estimate the internal flux.

IV. CONCLUSION

We have given an overview of the goals and status of the FRX-L experiment, as of spring 2003. This experiment represents a start on the road toward one realization of the MTF concept. MTF could be a relatively inexpensive and short term approach to an alternate fusion energy concept. Significant progress toward a target plasma has been achieved, with FRC parameters within a factor of 2–3 of the design goals. An outline of the technical achievements required to get to this experiment to its present state was briefly presented. A synopsis of typical recent data for the past year is shown. One shot was shown in detail and many plasma parameters are extracted from the dataset.

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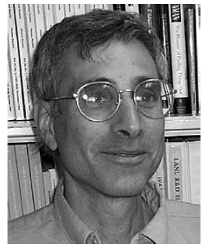

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