A High Density Field Reversed Configuration Plasma for Magnetized Target Fusion

T.P. Intrator *IEEE member*, J.Y. Park, J.H. Degnan *Senior IEEE member,* I. Furno,
C. Grabowski, S.C. Hsu, E.L. Ruden, P.G. Sanchez, J.M. Taccetti, M. Tuszewski, W.J. Waganaar,
G. A. Wurden *Senior IEEE member*, S.Y. Zhang

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 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 (nτ> 10^{13} s-cm^{-3} T> 5keV) 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—
Fusion energy, field reversed configuration, magnetized target fusion

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). 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 Figure 1. This strategy takes advantage of significant past scientific and technical accomplishments in MFE and Defense Programs research and should yield substantial plasma performance (nτ> 10^{13} s-cm^{-3} T> 5keV) using an available pulsed-power implosion facility at very modest cost.

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 β≈1, where β is the ratio of plasma particle pressure to external confining magnetic field. There is a large confining magnetic field, 5 Tesla prior to compression, and

figure 1 MTF schematic, showing plasma formation region and liner implosion section
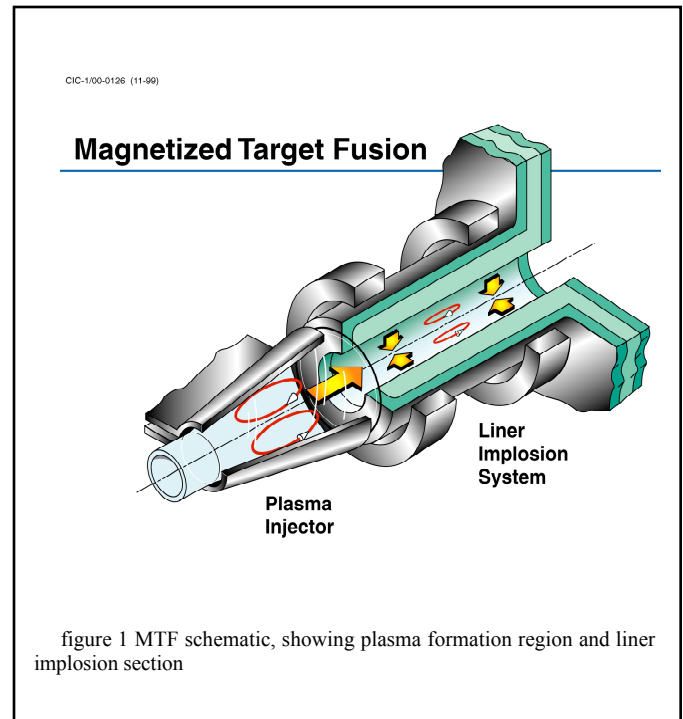
500 Tesla after compression. The auxiliary heating power level from the theta pinch formation is on the order of 100MW, and approximately 1000GW during flux conserver compression.

Among alternate fusion concepts, the choice of the FRC configuration for MTF also confers other advantages including
> Small size which results in reduced total construction cost. The heart of the device sits on a table top.
> Geometric simplicity because no captured magnetic coils or center stack ohmic transformer are required.

Magnetic simplicity because no   toroidal magnetic field, or linked magnets are required.

Heat exhaust handling includes a natural axial divertor

Advanced fuel potential could be realized at high β and large ion temperature

In a reactor, each pulse would utilize a fresh liquid first wall.

A repetition rate of 0.1 Hz, so that there would be time to clear the reactor chamber after each power pulse event.

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 demonstration 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 LANL, AFRL-Kirtland, LLNL, GA.

II. BACKGROUND: SCIENCE AND TECHNOLOGY

A. *Magnetized Target Fusion*

Magnetized Target Fusion (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 heat a magnetized target plasma, such as a spheromak or field-reversed-configuration (FRC), to fusion conditions. MTF involves plasma regimes intermediate (n $\sim 10^{19}$-10^{20} cm^{-3} and T $\sim$ 5 keV) between magnetic fusion energy (MFE) and inertial fusion energy (IFE) and seeks to capitalize on the advantages of this intermediate regime (described below) [1] [2] [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

$$P_{fusion} \approx n^2 <\sigma v> E_f \qquad (1)$$

where n is the density [m^{-3}] , $<\sigma v>$ is the fusion reaction rate [m^3 sec^{-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

$$P_{loss} \approx nT / \tau_E \qquad (2)$$

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

$$Q \approx n\tau_E <\sigma v> (E_f / T) \qquad (3)$$

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

$$\tau_E = R^2 / \chi \qquad (4)$$

Since system cost and size scale approximately with the plasma energy E$_p$, we can roughly estimate the cost as

$$E_p \approx nTR^3 \approx (\chi^{3/2}/ n^{1/2})(T^{5/3} Q / <\sigma v> E_f)^{3/2} \quad (5)$$

For a D-T fusion scenario, the right hand term on the right hand side is relatively constant because T$\approx$10keV, Q>1, $<\sigma v>$ 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], and which also offers some unique advantages over other possible targets.
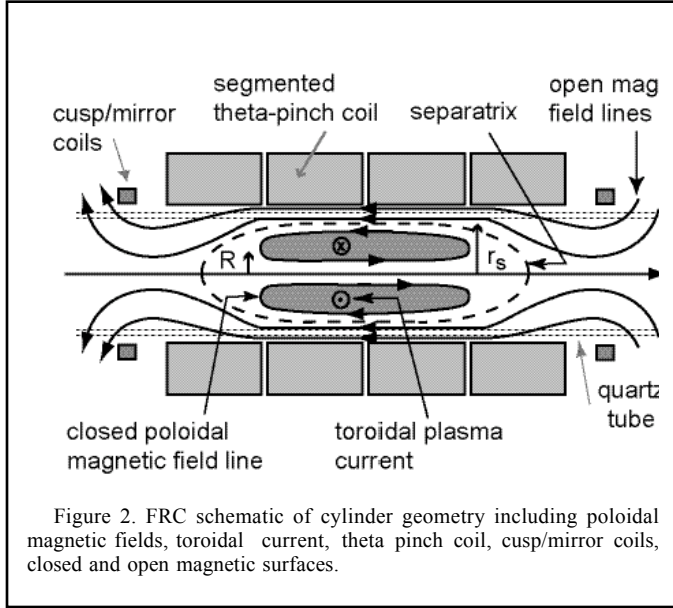
The FRC is an elongated, self-organized compact toroid state that has toroidal plasma current and poloidal magnetic field. In Figure 2 we indicate the FRC as a closed-field-line torus inside a separatrix radius r$_s$ with an open-field-line sheath outside the separatrix. FRC equilibrium balances plasma 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

$$<\beta> = 1 – x_s^2/2 \qquad (6)$$

where

$$x_s = r_s/r_c, \qquad (7)$$

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

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

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] [16] [17] [18] but the diagnostic methods and theoretical understanding were less complete in the 1960s-70s. Other desirable features include: (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 equation (6) and conserving particles yields an FRC volume that scales as $r_c^{2.4}$, i.e. more strongly than a 2D compression given by r_c^2 [20]. A full 3-D compression could be achieved with shaped liners, (3) FRC's 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 Tesla for FRX-L) that is frozen in during pre ionization (PI), and then radially shocked by another reversed main bank field that is much larger (3-5 Tesla 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). 2-D MHD MOQUI 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_θxB_z implosion velocity and consequently the Green-Newton [21] [11] [22] magnetic field. This field corresponds to equal Alfvén and ExB drift speeds at the edge

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

so that

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

In practical units $B_{GN}=1.88$ $E_\theta(kV/cm)^{1/2}$ $(A_i p_0(mTorr))^{1/4}$ where A_i is the ion mass in proton units, and for FRX-L operation at $p_0 \approx$ 40-80 mT, $B_{GN} \approx$ 0.5-0.7 Tesla. A high B_{GN} is desirable because B_{GN} limits the maximum trapped flux and hence the maximum plasma pressure in a theta pinch formed FRC. Increasing magnetic lift-off field B_{LO} that is trapped (when the main field reverses and the FRC "lifts off" the wall) relative to B_{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_{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 $B_{bias}/B_{GN} > 0.5$ 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 $\beta\sim1$
2. no or very little toroidal field
3. dominant cross-field diamagnetic current and flows
4. vanishing rotational transform, magnetic shear, 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] [26] [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 [28] [29] [30] [1] [2].

III. TECHNICAL PROGRESS OVERVIEW

During the last four years we have made major progress in creating a high density Field Reversed Configuration (FRC) target for MTF. We also successfully imploded two aluminum liners onto vacuum at Air Force Research Laboratory - Kirtland, demonstrating parameters appropriate for our proposed liner on plasma experiment [29] [30] [28].

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 2 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 pre-ionization 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 mid-plane 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 FRC's 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 figure 3a and a time expanded view of the bias, PI and main bank with ringing crowbar modulation in figure 3b. The crowbar modulation is being 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$_i$ > 400eV
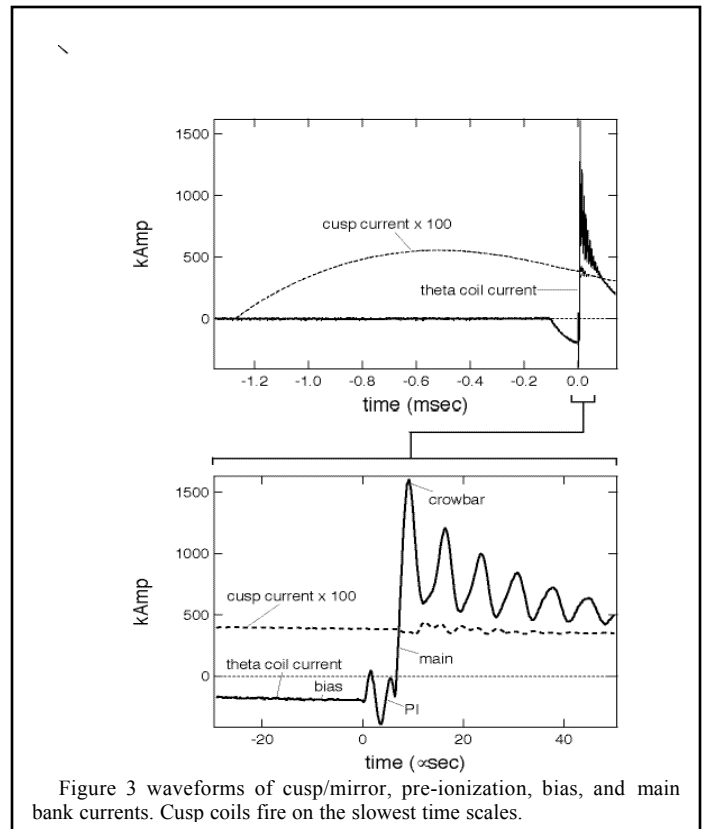

Figure 3 waveforms of cusp/mirror, pre-ionization, bias, and main bank currents. Cusp coils fire on the slowest time scales.

(200 eV), excluded flux >3 mWb (1 mWb), and internal flux ≈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 pre-fill pressure, exploration of pre-pre ionization schemes, and optimizing the timing sequence.

Even though high density FRC's 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 ~ 10^{17} cm^{-3}), temperature (to T$_e$≈T$_i$≈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. Pre-Ionization and formation

We benchmarked the Pre-ionization (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 Figure 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$_{eff}$≈1 historically) compared to a Z-pinch axial current discharge PI approach with internal electrodes. It provides a high (≈100%) level of ionization, and is more likely to work at our high fill pressure (40-80 mTorr).

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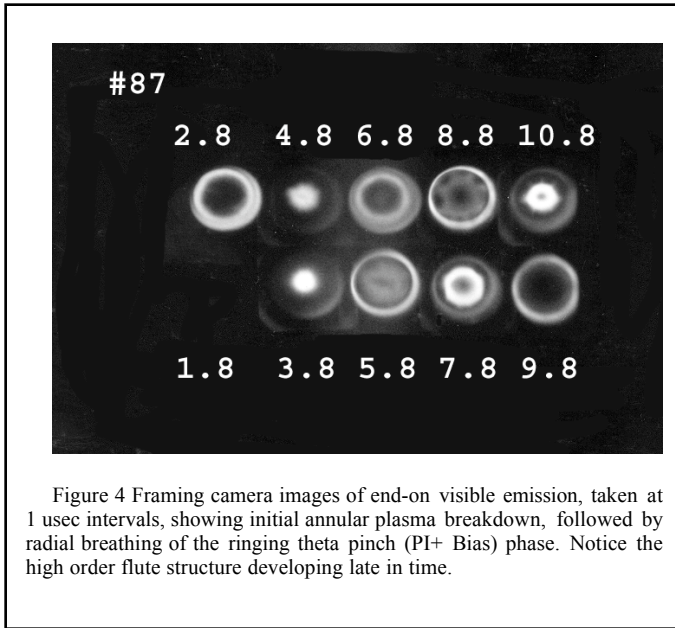
Figure 4 Framing camera images of end-on visible emission, taken at 1 usec intervals, showing initial annular plasma breakdown, followed by radial breathing of the ringing theta pinch (PI+ Bias) phase. Notice the high order flute structure developing late in time.

fill 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 μsec. The light emission profile can be seen to breathe radially as the confining magnetic field changes. At t=8.8 μsec, a flute like instability can be seen.

B. Density measurements

In Figure 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 multi chord interferometer. The central (solid line) and off axis (dotted line) chords show the n=2 rotational instability at t=16 μsec that triggers the demise of many FRC's, 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, ie similar plasma pressure. The separatrix shape is estimated by fitting an ellipsoidal shape to rs 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 Figure 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 microsec later with respect to the reversed main bank field. 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). [31] [32] [33] [21] [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 $\Phi_{exc}\approx3$ mWb and during decompressed equilibrium $\Phi_{exc}\approx1.5$ mWb. The internal flux estimated from the relation [11]

$$\Phi_{int}\approx \pi r_c^2 B_{ext}\,(x_s/2^{1/2})^{3+\varepsilon} \qquad (13)$$

is approximately 0.4mWb at formation and 0.15 mWb during equilibrium. Here B_{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 ε≈0.25 consistent with past FRC experiments at LANL [11]. The lift off flux Φ_{LO} is taken to be the value of estimated internal flux at the lift-off time. The lift off time t_{LO} is assumed to be the moment when the density from the interferometer starts to increase, eg in figure 5 density trace at t≈ 10 microsec.. The equilibrium internal flux is a smaller (15%) than expected fraction (30%) of the lift off flux, compared with a scaling estimate

$$\phi_{int}/\phi_{LO} \approx 0.85\ r_{wall}(m)\ P_0^{1/2}(mTorr) \qquad (14)$$

which favors large radius experiments instead of FRX-L. The modulation of B_{ext} from the crowbar switch can also be seen at the bottom of column 2 in figure 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 figure 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≈15 microsec. Flux loss may occur when the length (2x 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 <β> condition and pressure balance yields for figure 5 an average temperature $<T_e+T_i> \approx 300$ eV for formation and ≈ 200 eV for the equilibrium period. The apparent modulation in temperature after t=15.5μsec 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 $\tau_N \approx 10$ μsec can be estimated from the time history of particle inventory (right hand column), inferred from interferometer density multiplied by an assumed ellipsoidal separatrix volume
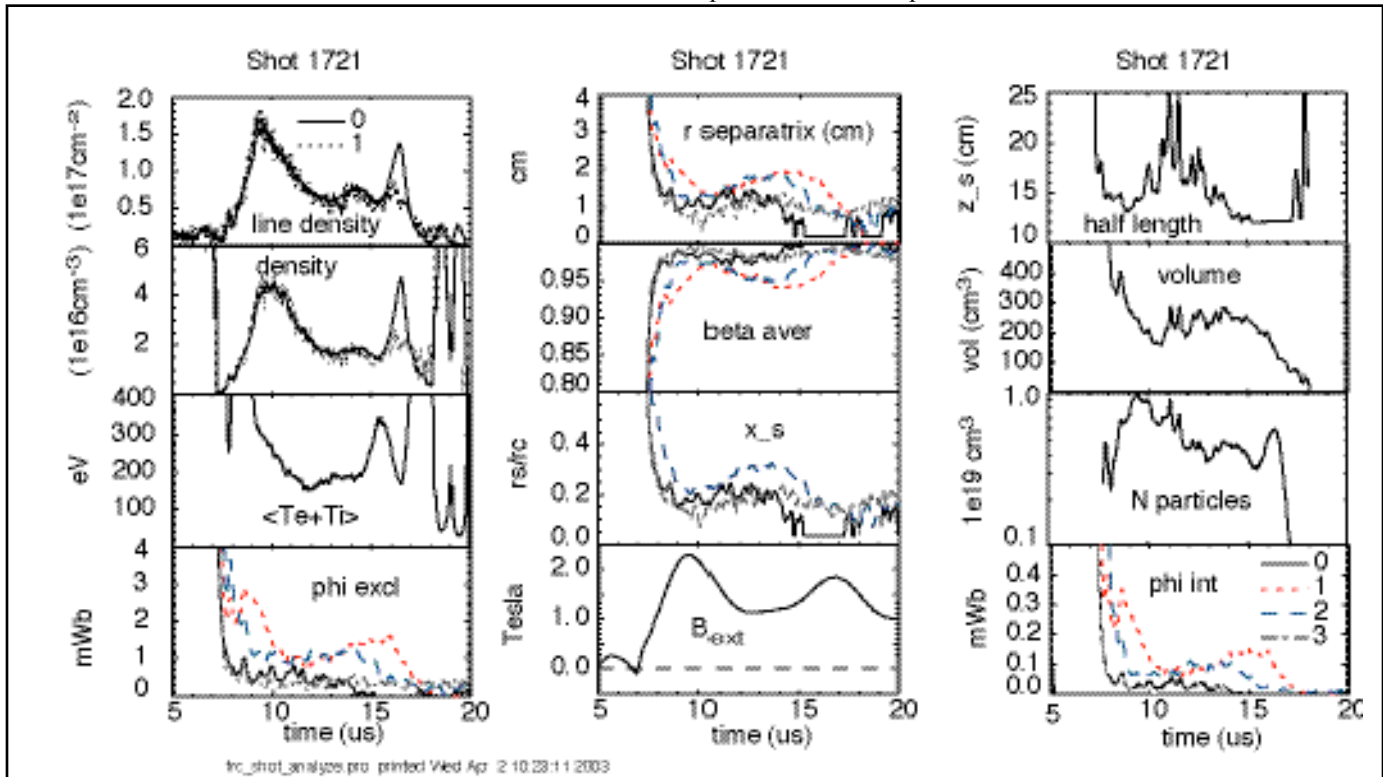
provide an independent measurement of the electron

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

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 $B_{ex.}$ which is a physically reasonable behavior. This gives confidence about our physical assumptions (elliptic shape, r_s measurement, density=line density/$2r_s$) built into this estimate.

E. Equilibrium characteristics

Separatrix radius for 4 axial locations is inferred from excluded flux data. The excluded flux array together with the multi-chord 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, equation (6) for volume-averaged beta $<\beta>=1-x_s^2/2$ [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 figure 5 particle inventory and average energy per particle (temperature).

F. Radial profiles of density

Multi-chord interferometer data can be inverted to estimate the density profiles. Figure 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 $r\approx0$ and flat near $r\approx R$ as expected. Eventually, the new Thomson scattering diagnostic will

temperature at six axial spatial points on each shot. This point data will be compared 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, including the resistivity at the field null and separatrix [35-37].
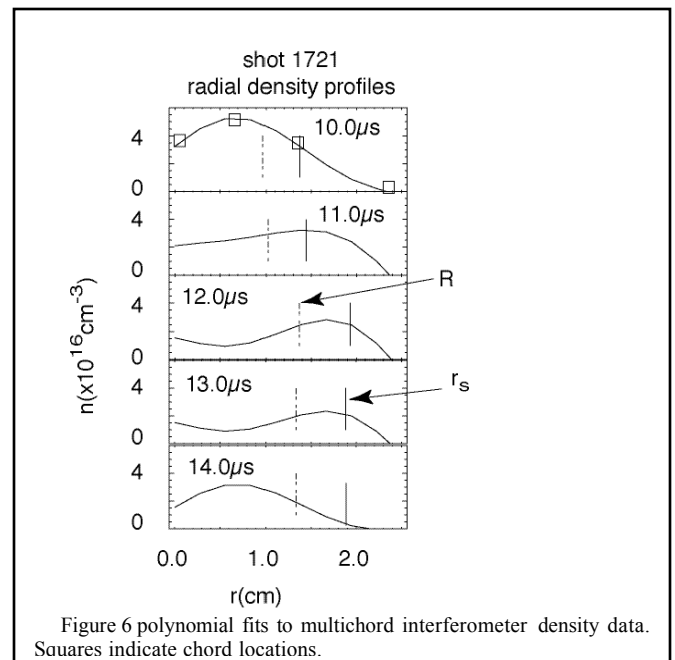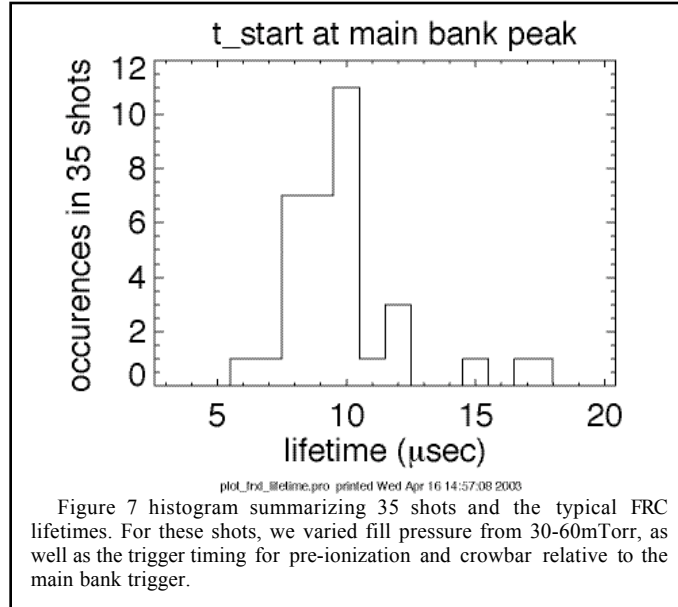

Figure 6 polynomial fits to multichord interferometer density data. Squares indicate chord locations.

G. Configuration lifetimes

Several campaigns have been undertaken to explore the experimental knobs available to us. Surveys of fill pressure have 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 Tesla. From a database of 35 shots, for "typical" operation, FRC lifetimes are shown in the histogram

of Figure 7, and are mostly in the range of ~10 μsec, but

Figure 7 histogram summarizing 35 shots and the typical FRC lifetimes. For these shots, we varied fill pressure from 30-60mTorr, as well as the trigger timing for pre-ionization and crowbar relative to the main bank trigger.

extend towards 20 μsec in a few cases. For these shots, we varied fill pressure from 30-60mTorr, as well as the trigger timing for pre-ionization 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 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 Nov 2002 –April 2003 have resulted in $\approx$ 500 shots with $\approx$ 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 FRC's. 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

Parameter	design spec	present FRXL Peak	present FRXL 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

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.

FRX-L experiment, as of spring 2003. This experiment represents a start on the road towards one realization of the Magnetized Target Fusion concept. MTF could be a relatively inexpensive and short term approach to an alternate fusion energy concept. Significant progress towards 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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NOTE: There are many preprints and papers http://wsx.lanl.gov Particularly http://wsx.lanl.gov/Publications/mfe_papers.html and also at http://fusionenergy.lanl.gov

T. Intrator was born in New York City in 1952. This author became a Member (M) of IEEE in 2003. He recently joined Los Alamos National Laboratory, Los Alamos, NM as a Member of the Technical Staff (1999), to be project leader for the LANL Magnetized Target Fusion FRX-L effort. He also has been Principal Investigator for the Reconnection Scaling Experiment (RSX) at LANL, which is an (internally-funded) unique device to investigate MHD plasma physics including magnetic reconnection. Physics, engineering and teaching work at the University of Wisconsin included a host of basic physics tabletop experiments and magnetic fusion devices. A sojourn as visiting scientist at Bell Laboratories Murray Hill NJ (1987), was followed by a year as Visiting professor at the Université de Grenoble, France (1989). He received his Ph.D. in plasma physics from the Univ of Colorado in 1982. Dr Intrator is also a member of APS, AGU. He recently

won (2001) a LANL Student Mentor Award, and leads the effort to develop summer student programs in P-24.

Jaeyoung Park received the Ph.D. degree in astrophysical sciences from Princeton University, Princeton, NJ. He is currently a Technical Staff

Member at Los Alamos National Laboratory, Los Alamos, NM, working on applied plasma physics and innovative confinement concepts for nuclear fusion. His current research interests are plasma diagnostics, atmospheric pressure plasmas and plasma-based neutron source development.

Dr. Glen A. Wurden is presently Team Leader of the MFE Section in the P-24 Plasma Physics Group at Los Alamos, and acting OFES Program Manager at LANL, was born on Sept. 9, 1955 in Anchorage, Alaska. He attended public schools in western Washington, and went to the University of Washington with a National Merit Scholarship. There he earned three simultaneous B.S. degrees, in Physics, Mathematics, and Chemistry, summa cum laude (1977), graduating with the highest class honors as President's Medalist. He was awarded a National Science Foundation Graduate Fellowship, and chose Princeton University to specialize in Plasma Physics for his M.S. (1979) and Ph.D. (1982) Degrees. He is a member of Phi Beta Kappa, the APS, and a senior member of the IEEE. His research interests include magnetized target fusion, plasma diagnostics, alternate confinement concepts, including burning plasma issues.

Chris Grabowski was born in Dayton, OH, on October 8, 1966. He received the B.S. degree in electrical engineering from Texas Tech University, Lubbock, in 1988 and the M.S. and Ph.D. degrees in electrical engineering from the University of New Mexico, Albuquerque, in 1990 and 1997, respectively. During 1991 and part of 1992, he worked as a Research Student in the Pulsed Power Laboratory at Kumamoto University, Kumamoto, Japan, studying inductive energy storage pulsed power generators. After graduation, he worked as a Postdoctoral Researcher at both the Weizmann Institute of Science in Rehovot, Israel, and at Cornell University, Ithaca, NY, studying plasma spectroscopy and high-power traveling wave tube amplifiers, respectively. Currently, he is a senior staff engineer with Science Applications International Corporation, Albuquerque, where he has had the opportunity to work on a wide variety of pulsed power projects.

James H. Degnan (A'90–M'99–SM'99) received the Ph.D. degree in physics in 1973 from the Department of Physics and Astronomy, University of Pittsburgh, PA, where he did his thesis work on experimental nuclear reaction studies. Since 1973, he has been with the Air Force Research Laboratory (AFRL) and its predecessors, Air Force Weapons Laboratory and Phillips Laboratory. There he designed, conducted, and directed research on high energy density plasmas, radiation diagnostics, and pulsed power. His recentwork includes magnetic pressure implosions of cylindrical and spherical metal shells for plasma compression. He is presently a senior physicist (GS-15=DR-IV) and Technical Advisor of the Pulsed Power Branch (DEHP) in the High Power Microwave Division of the Directed Energy Directorate of the Air Force Research Laboratory

J. Martin Taccetti (M'88) was born in Buenos Aires, Argentina. He received the B.S. degree in physics from SUNY, Stony Brook, in 1990, and the Ph.D. degree from the University of Maryland, College Park, in 1998. He

performed his thesis work on free-electron lasers at the Naval Research Laboratory, Washington, DC. He is presently a staff member of the Plasma Physics group, Los Alamos National Laboratory, Los Alamos, NM, where his research involves the study of magnetized target fusion as an approach to fusion.

B. Waganaar, Bill Waganaar is the lead operator and electro-mechanical technician for the FRX-L Magnetized Target Fusion experiment at Los Alamos National Laboratory. He has been responsible for or involved with most aspects of Pulsed Power experimental operations at the Laboratory for twenty years including design, fabrication, and trouble-shooting. He served in the US Navy for four years as an Aviation Electricians Mate and then studied Electronics at New Mexico Highlands University. He was employed at Eberline Instrument Corporation in Santa Fe, New Mexico, for ten years as an Electronics Technician before his Laboratory employment..

S.Y. Zhang Dr. Shouyin ZHANG got his PH.D in plasma physics in 2000 at the Institute of Plasma Physics (ASIPP), the Chinese Academy of Sciences. His PH.D thesis on developing an innovative fast-scanning millimeter wave heterodyne radiometer system for ECE measurements on HT-7 superconducting tokamak won him a Chinese national award of Academician/Prof. CAI Shidong Plasma Physics Prize in 2000 from China Plasma Physics Society. The techniques developed are also patented. Before he joined the Plasma Physics Group at LANL as a Postdoctoral Research Associate in Nov.2001, Dr. ZHANG was a principal investigator on tokamak plasma physics and diagnostics. He received his B.S. degree from the University of Science and Technology of China in 1988, and after that he had been doing plasma diagnostics and plasma physics experiments on HT-series tokamaks. Dr. ZHANG's rich research experiences and accomplishments on tokamak plasma physics are illustrated by his publications, national awards and approved China Patent. Dr. ZHANG is currently diagnosing and studying the formation of high density field reversed configuration (FRC) plasma for Magnetized Target Fusion program on FRX-L device in the Plasma Physics Group of Los Alamos National Laboratory.

I Furno has a Master Degree Summa cum Laude in Nuclear Engineering at the Politecnico di Torino, February 1995. Ph.D. in Plasma Physics at the Ecole Politechnique Federale de Lausanne, Switzerland, July 2001. Currently, PostDoctoral Appointee in P-24 at LANL. Furno's research work mainly focuses on experimental plasma physics in magnetically confined laboratory plasmas for thermonuclear fusion and for basic plasma physics research. Furno has an extensive knowledge of plasma diagnostics and has designed and successfully implemented a number of systems fully integrated into the Tokamak á Configuration Variable in Lausanne. During his Ph.D., Furno studied heat and particle transport induced by magnetic reconnection during sawtooth activity in radiofrequency heated tokamak plasma. During the last year, Furno worked on RSX and FRX-L in P-24 as PostDoctoral appointee, developing plasma diagnostics and acquisition systems, and acquired a broad knowledge of the innovative plasma gun technology used to produce the plasma in the device. Presently, Furno is also involved in a project to develop miniature (sub mm size) magnetic detectors in collaboration with the National High Magnetic Field Laboratory and Sandia National Laboratory.

Furno has published about 40 works (26 on international refereed journals).

S. C. Hsu received his B.S. (Electrical Engineering, 1993) from UCLA and his Ph.D. (Plasma Physics, 2000) from Princeton University. His thesis research was on the experimental investigation of ion heating during magnetic reconnection. Afterward, he brought a U.S. Dept. of Energy Fusion Energy Postdoctoral Fellowship to Caltech, where he built and used a simple magnetized coaxial gun to study the dynamics of spheromak formation and also magnetic collimation related to astrophysical jets. In December, 2002, Scott joined the P-24 Plasma Physics Group at Los Alamos as a Reines Fellow in Experimental Sciences. He is now continuing basic experimental plasma physics research with an eye toward magnetic fusion energy and plasma astrophysics applications. Scott was a co-recipient of the 2002 Award for Excellence in Plasma Physics Research, given by the American Physical Society.

E.L. Ruden, Member, IEEE. Dr. Ruden received his Ph.D. in physics studying plasmas from UC, Irvine in 1988. Since then has performed research in the area of high energy density states of matter for the Air Force Research Laboratory's Directed Energy Directorate, and its organizational predecessors. He has developed several interferometric systems for the diagnosis of plasmas using coherent radiation sources across a broad spectrum: millimeter wave, far IR,

visible, and UV. In addition, he has extensive experience in experimental, analytic, and computational efforts involving continuum dynamics of all phases of matter.

M. Tuszewski received a Ph.D. in Nuclear Engineering, 1976, from the University of California, Berkeley. He is a Los Alamos National Laboratory Fellow and a Fellow of the American Physical Society. He is a noted authority on Field Reversed Configurations, and more recently has been interested in inductively coupled plasmas and space plasmas. He has obtained 4 patents.

P. Sanchez received a BS from New Mexico State University, and has many years of experience in electrical engineering. He has designed and built analog, digital, pulsed power control, computer control, and interface electronics.