Progress on the FRX-L FRC Plasma Injector at LANL for Magnetized Target Fusion

G. A. Wurden, P. N. Assmus, W. J. Feinup, T. P. Intrator, M. C. Langner, R. J. Maqueda, K. J. Scott, R. E. Siemon, E. M. Tejero, J. M. Taccetti, M. G. Tuszewski, Z. Wang, S. Y. Zhang, Los Alamos National Laboratory, Los Alamos, NM 87545 USA

C. Grabowski, S. K. Coffey, J. H. Degnan, D. Gale, E. L. Ruden, W. Sommars
Air Force Research Laboratory, Kirtland AFB, Albuquerque, NM USA

E-mail: wurden@lanl.gov

Abstract

The FRX-L Field Reversed Configuration plasma is now operational at Los Alamos National Laboratory. The goal of the project is to demonstrate the production of suitable FRC target plasmas for later MTF (Magnetized Target Fusion) implosion experiments which will first be carried out at the Air Force Research Laboratory in Albuquerque, New Mexico, in a few years' time. Expected plasma parameters in the 4 cm diameter, 30 cm long FRC are n_e~10^{17} cm^{-3}, T~100-300 eV, at 4-5 Tesla fields, with a lifetime of ~20 microseconds. The system includes a 0.5 T bias field, 70 kV 250 kHz ringing pre-ionization, and a 1.5 MA, 200 kJ main-theta-coil bank. Maxwell rail gap plasma switches are used to start the PI bank, the main theta coil bank, and to crowbar the main bank. Initial results using the first diagnostic set of excluded flux loops, B-dot probes, visible light diodes, a fiber-optically coupled gated-intensified visible spectrometer, and a 3.3 micron quadrature interferometer are presented. Future diagnostics include end-on bolometry, Thomson scattering, and a multi-chord fanned HeNe side-on interferometer. Multi-turn cusp and guide coils will be added later this year, to enable translation experiments into a cylindrical metal liner.

We have recently completed the assembly of FRX-L (Field Reversed eXperiment, Liner) at LANL (Los Alamos National Laboratory). The purpose of this experiment is to demonstrate formation and translation of a suitable FRC plasma for use in later Magnetized Target Fusion implosion experiments[1]. In order to achieve substantial plasma performance using liner implosions, defined as T_i~ 5 keV, $n_e \tau_E$~10^{13} cm^{-3} sec, using a 10× radial compression of the nominally cylindrical plasma, we need to start with an FRC with the parameters in Table 1. It is the goal of the FRX-L experiment to form, and measure the characteristics of such a compact, high-density, pre-compression plasma. The FRC design point assumes a conical theta pinch coil of radius 4 - 6 cm; length 30 cm, using the LANL COLT capacitor bank, having a single feed at 40 kV (× 2 to 80kV due to Marx configuration); with a corresponding electric field of ~1 kV/cm under the coil. The main field rise-time will be 2.5-3 μs, and we would use a deuterium gas fill pressure of ~100 mTorr, and a lift-off bias field of 0.4 T.

Table 1. Zero-D calculations of FRC parameters

Parameter	**Before Compression (initial proposal)**	**After Compression (endpoint for initial proposal)**
coil radius (cm)	5	0.5
Separatrix radius (cm)	2.3	0.2
coil length (cm)	30	30
Separatrix length (cm)	30	4.2
B external (T)	5.4	520
peak density (10^{17} cm^{-3})	1.2	350
T_e (keV)	0.3	8.6
T_i (keV)	0.3	10.6
plasma energy (kJ)	7.4	80
τ_E (μs)	28	4
particle inventory (10^{19})	5.0	1.7
internal flux (mWb)	1.0	0.64
S*	23	35
E	6.7	11
S*/E	3.5	3.3

From simplified Zero-D code parameters of subsequently compressing this plasma with the Shiva facility, the equivalent DT fusion yield is estimated at 0.1 MJ, (or a neutron yield 3×10^{16} DT neutrons), corresponding to a Q (fusion/liner energy) ~ 0.05. Conservatively, this performance represents more than a ten-fold increase of the $n\tau T$ triple product compared to the best existing FRC data. To a certain degree, our initial task is to replicate the target plasma performance that has already been demonstrated in the late 1960's at the Naval Research Laboratory[2].

Our near term experimental efforts are to form and characterize the compact, high density FRC plasma, first in a quartz tube, and later translated into an aluminum liner. LANL and the Air Force Research Laboratory in Albuquerque makeup the experimental team who are developing the FRC plasma target at LANL and later liner experiments[3] at the AFRL Shiva-Star facility for energetic liner compression. The FRX-L experiment is controlled by a Sun workstation running LabView software, which communicates to CAMAC and scope-based digitizers using GPIB interfaces. It performs real-time readout of banks charging, and monitoring of system interlocks. Data is then written to an MDS-Plus[4] database for convenient X-Windows based viewing and data manipulation using IDL software. The turbo-pump based vacuum system achieves base pressures in the 1×10^{-8} Torr range, and also incorporates a roughing pump for post-shot pump-out of the high (~100 mTorr D_2) fill pressures. At the moment we are using static gas filling, but later will have puffed capability as well. Each of the system components of the experiment is relatively mobile (usually wheel-mounted), in anticipation of a future move of the plasma injector system (FRX-L) to a large capacitor bank liner driver (such as Shiva Star or Atlas).

Figure 1: Block diagram of the main elements of the FRX-L experiment.

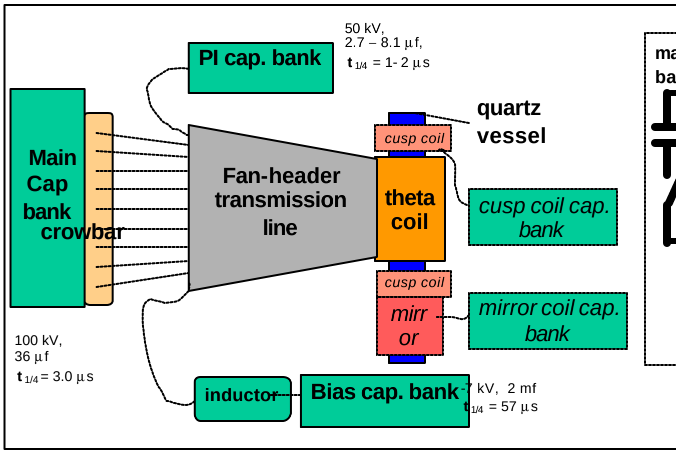
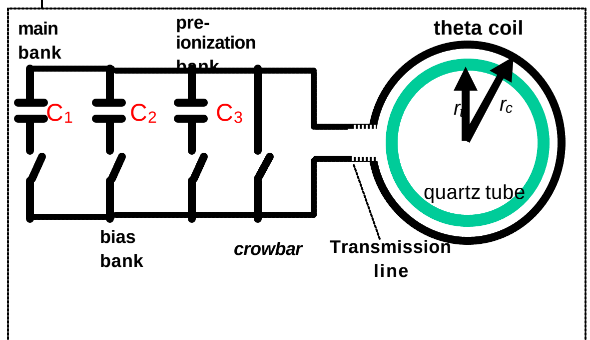


Figure 2: Simplified electrical schematic



We have been firing so-called "pre-ionization" plasmas since April 2001. These exercise the computer control system, the vacuum and gas-handling systems, the ignitron-switched slow Bias bank, and the rail-gap switched high frequency ringing PI bank, using a so-called "test header" collector plate. In the meanwhile, other work progressed on the design and construction of the large, low inductance "fan header transmission plates", and the multiple unit rail-gap crowbar switch for the Main bank. To get started with basic diagnostics[5], we installed B-dot probes, excluded flux loops[6], various voltage monitors, two filtered visible light monitors (PMT and diode-based), a gated intensified Optical Multichannel Analyzer (Princeton Applied Research 1460 system) on a 0.3 meter McPherson 216 spectrometer (with modern LabView readout to MDS-Plus), a resurrected 3.39 micron HeNe single chord laser interferometer from FRX-C (which is good for about 200 microseconds before vibrations hit it), and Imacon 700/790 Polaroid film-based fast end-on visible light framing cameras.

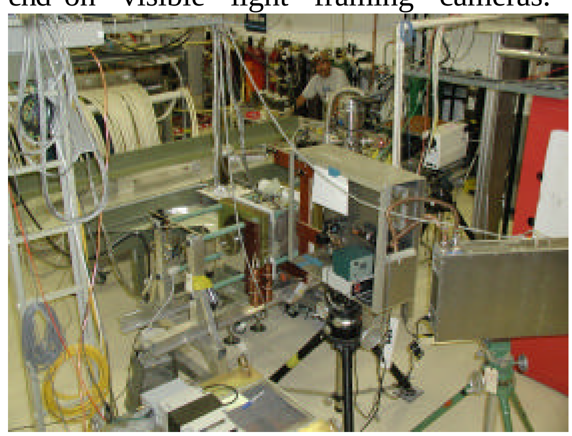


Figure 3: A photo of the new FRX-L laboratory (9/2001), with the FRX-L FRC in the middle of the photo, partially hidden in the foreground by the 3.39 micron laser interferometer, and in the background by the fan-shaped parallel-plate header which feeds currents to the 1-turn theta-coils.

We focused several months of effort on the pre-ionization (PI) technique[7], because it will affect the quality of the eventual FRC..

Starting with the ringing PI (which uses the main theta pinch coils, without any internal hardware or extra antennas), we found that using 6 capacitors in the PI circuit, which gives us enough current at 50 kV charge to zero cross a 0.5 Tesla bias field, would not give us reliable gas breakdown. On the other hand, 2 capacitors (250 kHz ringing frequency), charged to the same voltage, works well at all pressures, but can only zero cross up to ~0.25 Tesla bias fields. Consequently, we will be forced towards higher charging voltages (in principle, we can go up to 100 kV if necessary), and using more (e.g., 4) capacitors in the PI circuit. Waveforms of the bias and PI circuit tests are shown in Figure 4.

Figure 4: Variation of the pre-ionization bank ringing frequency as a function of the number of capacitors in the circuit (1, 2, and 6). (The traces are offset for display purposes).

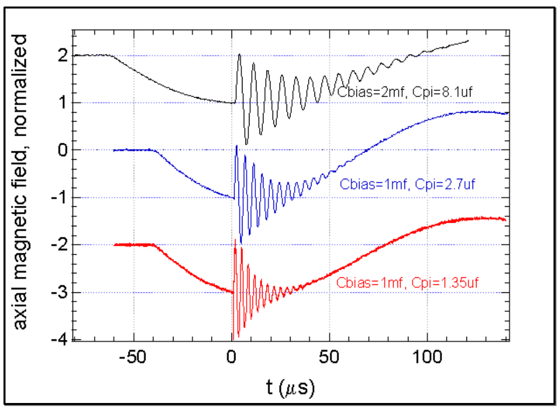
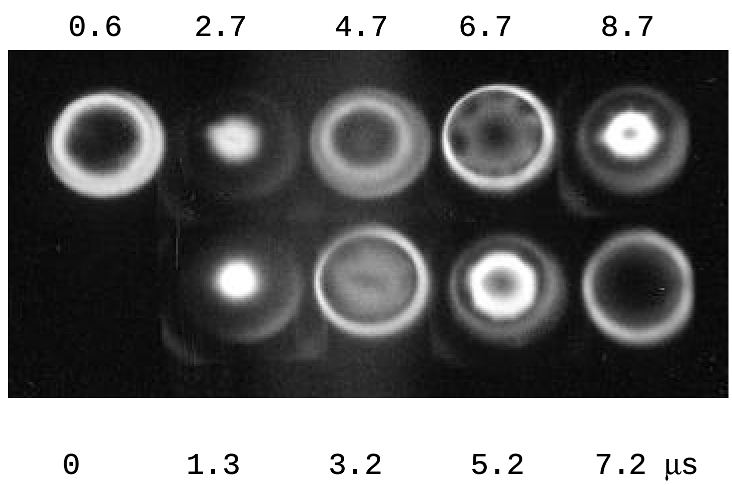


Figure 5: End-on visible light images from shot 87, P=43 mTorr Deuterium. The timings of frames 1-10 are indicated in microseconds, respectively. A high order asymmetry is visible by frames 7-8. Reflections on quartz tube light-up the outer circular boundary.



It is clear from end-on framing camera pictures (Fig. 5) that one does not want to wait "too long" to fire the Main bank, otherwise instabilities grow which disturb the symmetry of the PI plasma. These asymmetries are most evident towards the lower end of the fill pressure range which we have explored (probably because that is where collisional effects are the smallest). An example sequence of white light framing pictures is shown in Figure 5, and a high order asymmetry is developed by the 7th and 8th images. We have conducted density scans from 20 mTorr to 320 mTorr fill pressures, which span the anticipated range of interest for the eventual high-density FRC operation. Density and light traces from a 260 mTorr static fill deuterium PI+Bias discharge are shown in Figure 6.

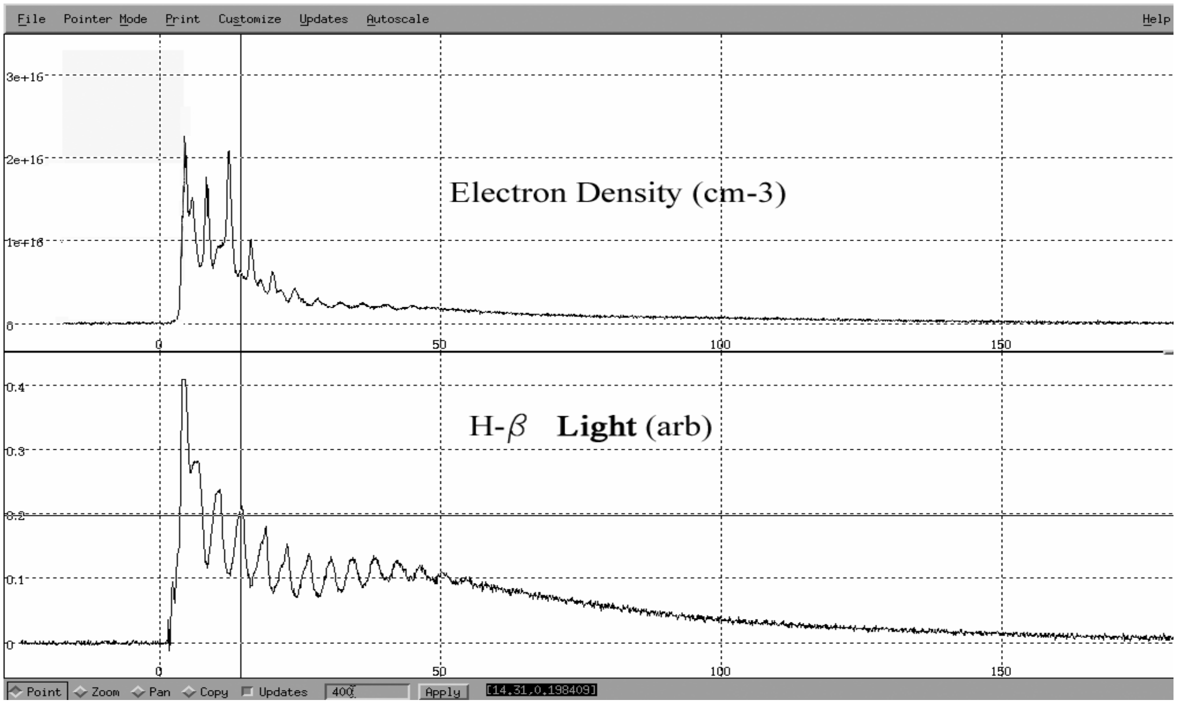


Figure 6: Line averaged electron density (assuming 10 cm path length) from the radially viewing 3.39 micron laser interferometer, and a radial view of H-beta light emission using a filtered photomultiplier tube, as a function of time (microseconds) during a 260 mTorr Deuterium PI+Bias bank shot on FRX-L. The 250 kHz oscillations visible in the density and light are a result of the ringing theta-pinch preionization technique, using two 1.35 microfarad capacitors charged to 50 kV.

Recently, we have been operating with the full main bank, to make actual high energy FRC plasmas. Also, the new AFRL mutli-chord (presently operating with 2 chords) visible He-Ne interferometer has been installed. With 5x shorter wavelength, and 80 MHz quadrature operation, it provides better data (fewer fringes, and fewer "fringe skips") during high-density main bank operation. Later this year, we anticipate performing FRC studies at high density and energy, using a full suite of plasma diagnostics, prior to translating the FRC plasma into a "dummy" aluminum liner section (which we have yet to design). The near term future diagnostic additions include eight-chord interferometry, 3-point Thomson scattering, end-on bolometry, and end-on x-ray framing imaging. From Nov. 2001 to Jan. 2002, although we have fired a few high energy FRC plasmas, we mainly dealt with troubleshooting triggering problems (crosstalk & grounding issues) between the three different capacitor banks, and a main bank pre-fire which destroyed a number of rail-gap switches.

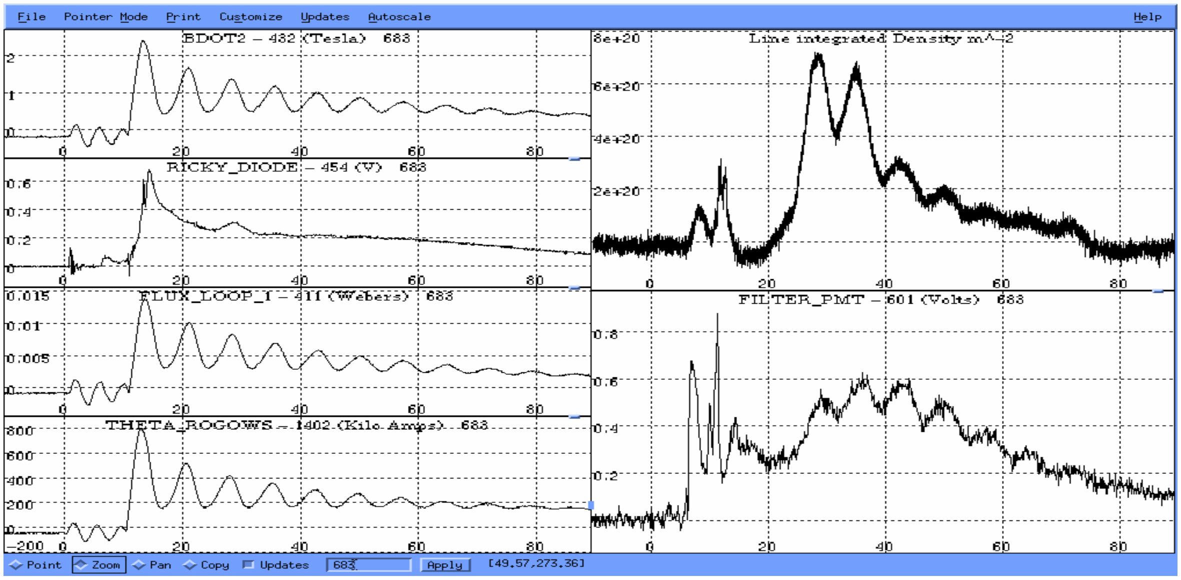


Figure 7. A recent main bank shot #683, at 35kV bank charge voltage, with theta coil current at the 800 kA level, the plasma lasting about 50 microseconds, and a line averaged density of ~7x10^{15} cm^{-3}.

These problems are now solved (2/2002), and experiments with FRC's formed with the main bank and crowbar are continuing, as shown in Figure 7.

The construction of the machine has also been made possible by the work of William Waganaar, Daniel Begay, Robert Newton, Ed Mignardot, George Sandoval, and others at LANL. Ideas concerning Magnetized Target Fusion have been documented in many prior papers and proposals, and are not listed here. This work is supported at LANL by the US DOE Office of Fusion Energy Sciences through contract #W-7405-ENG-36.

REFERENCES

1. Wurden, G.A., et al., *Magnetized Target Fusion: A Burning FRC Plasma in an Imploded Metal Can*, in Journal Plasma Fusion Research SERIES. 1999: Toki, Japan. p. 238-241.

2. McLean, E.A., A.D. Anderson, and H.R. Griem. *Measurement of Plasma Density and Particle Losses in a Large Theta Pinch*. in *APS Topical Conference on Pulsed High-Density Plasmas*. Sept. 29, 1967. LA-3770 TID-4500, Los Alamos, NM: Los Alamos National Laboratory.

3. Degnan, J.H., et al., *Implosion of Solid Liner for Compression of Field Reversed Configuration*. IEEE Transactions on Plasma Science, 2001. **29**(1): p. 93-98.

4. Stillerman, J.A., et al., *MDSplus data acquisition system*. Rev. Sci. Instrum., 1997. **68**(1): p. 939-941.

5. Wurden, G.A., et al., *Diagnostics for a magnetized target fusion experiment*. Rev. Sci. Instrum., 2001. **72**(1): p. 552-555.

6. Tuszewski, M., *Excluded flux analysis of a field-reversed plasma*. Phys. Fluids, 1981. **24**(11): p. 2126-2127.

7. Armstrong, W.T., et al., *Theta-pinch ionization for field-reversed configuration formation*. Appl. Phys. Lett., 1981. **38**(9): p. 680-682.