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

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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.

1 Introduction

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, $n_e t_E$~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.

Table 1. Zero-D calculations of FRC parameters

Parameter	**Before Compression (initial proposal)**	**Before Compression (latest model of actual system)**	**After Compression (endpoint for initial proposal)**
coil radius (cm)	5	5	0.5
Separatrix radius (cm)	2.3	2	0.2
coil length (cm)	30	30	30
Separatrix length (cm)	30	30	4.2
B external (T)	5.4	4.5	520
peak density (10^{17} cm^{-3})	1.2	.6	350
T_e (keV)	0.3	.15	8.6
T_i (keV)	0.3	.15	10.6
plasma energy (kJ)	7.4	3	80
τ_E (μs)	28	15	4
particle inventory (10^{19})	5.0	2	1.7
internal flux (mWb)	1.0	0.5	0.64
S*	23	15	35
E	6.7	7	11
S*/E	3.5	2.1	3.3

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 ($\times 2$ 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 300 mTorr, and a lift-off bias field of 0.4 T. 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) ~ 0.1. 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]

2 Construction

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 and later liner experiments[3] at the AFRL Shiva-Star facility for energetic liner compression. The FRX-L experiment is located at LANL in what was formerly known as the "Colt" facility, and reuses the main capacitor bank, screen room, and computing facility. [4]

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

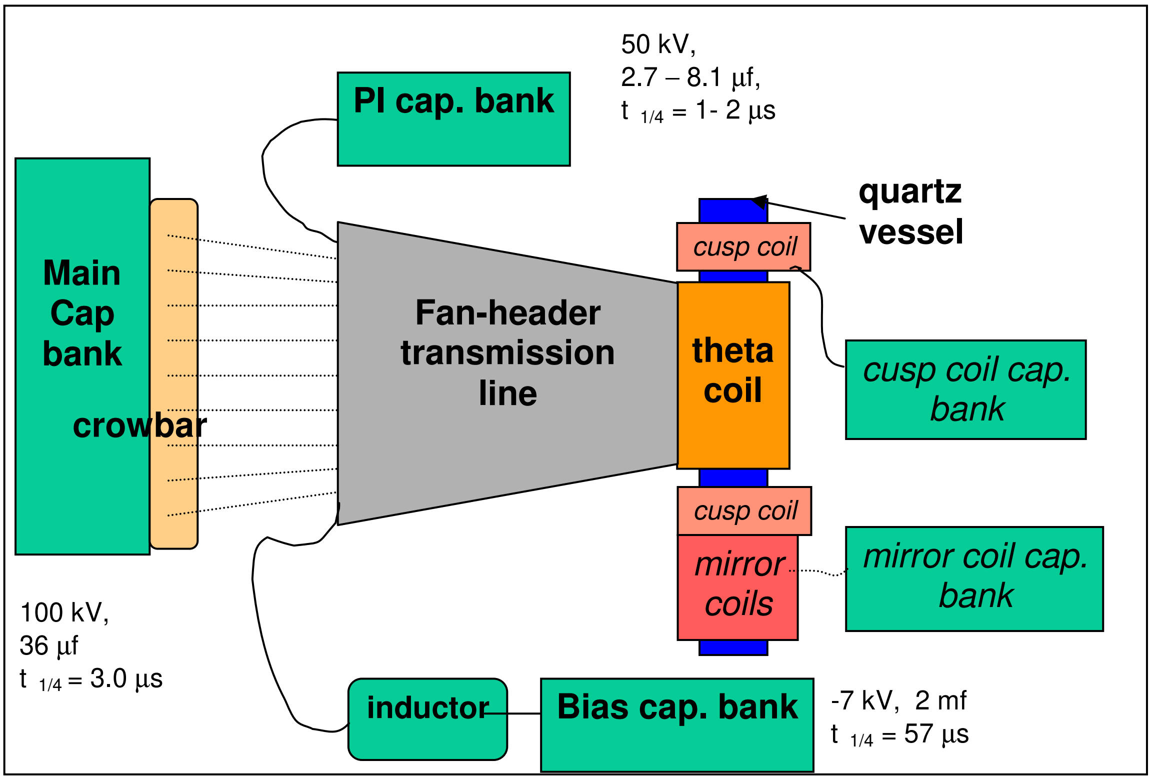
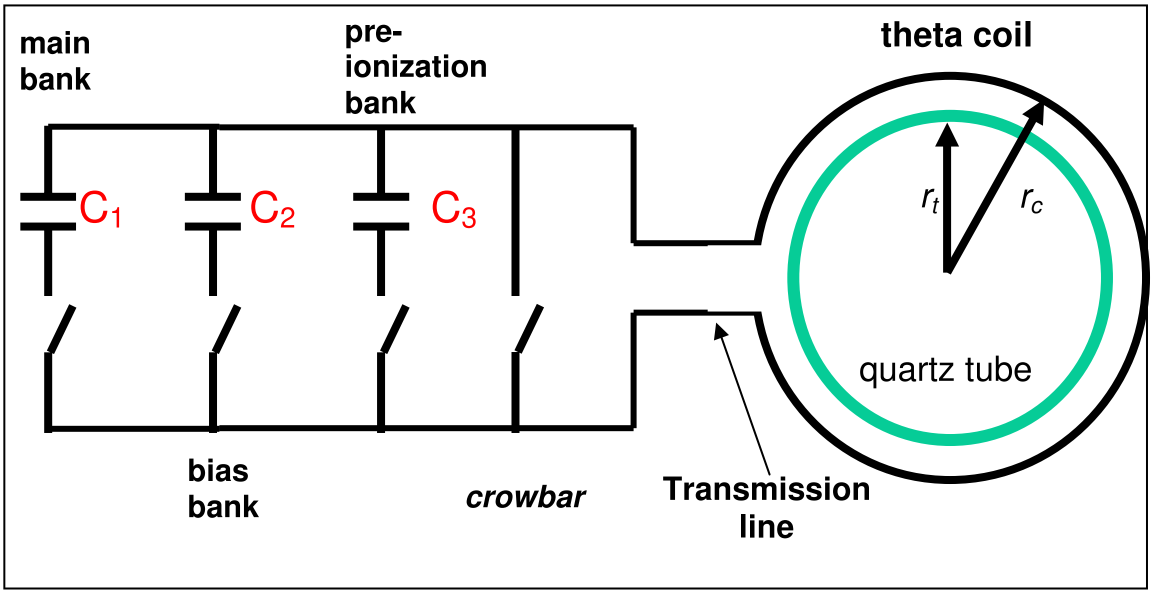


Figure 2: Simplified electrical circuit of the formation region of the FRX-L experiment.



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[5] database for convenient X-Windows based viewing and data manipulation using IDL software. The turbo-pump based vacuum system achieves base pressures in the $1x10^{-8}$ 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).

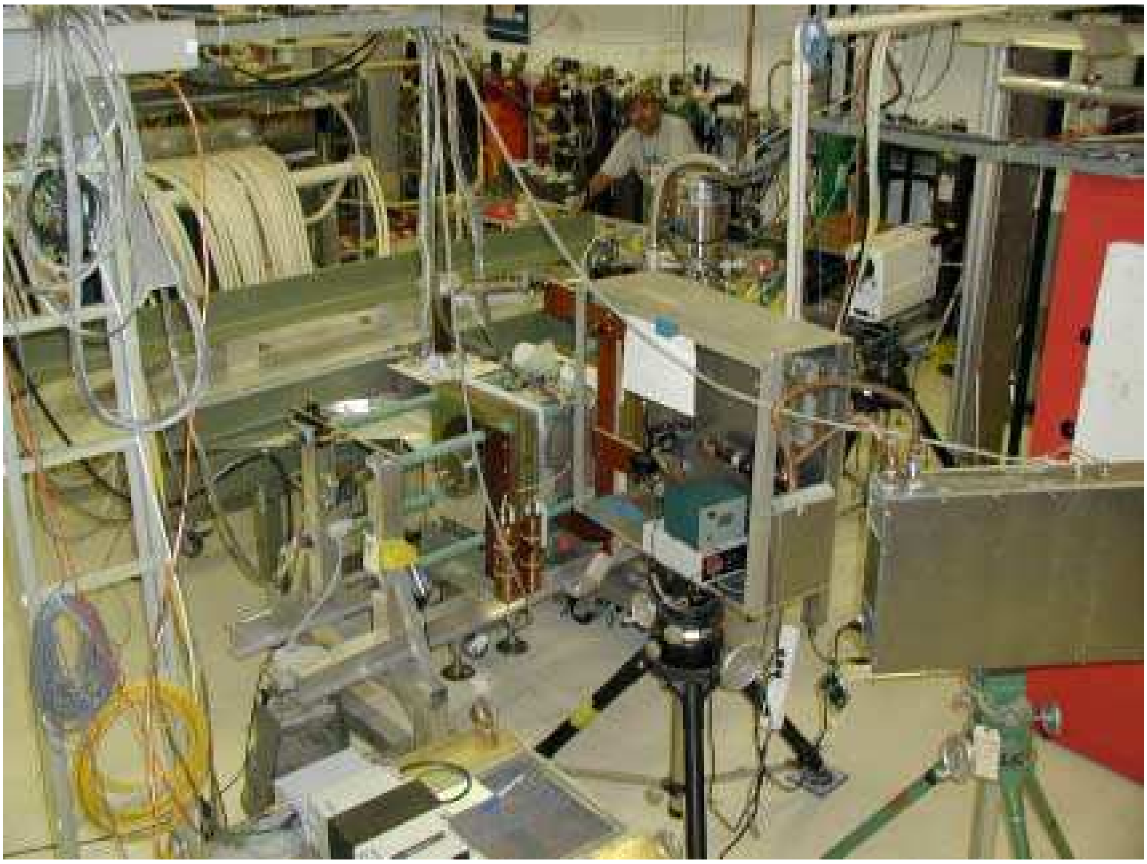


Figure 3: A recent picture of the new FRX-L laboratory, with the FRX-L FRC in the middle of the photo, partially hidden in the foreground by the 3.39 micron laser interferometer, and in the background by the fan-shaped parallel-plate header which feeds currents to the 1-turn theta-coils.

3 Initial Operation

In order to gain experience, and to debug the new hardware, 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[6], we installed B-dot probes, excluded flux loops[7], 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 Poloroid film-based fast end-on visible light framing cameras.

We have focused on the pre-ionization (PI) technique[8], because it will affect the quality of the eventual FRC. Possibilities for pre-ionization include ringing theta-pinch PI, z-pinch PI, and/or multi-MegaHertz RF methods. 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 plenty of 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. We intend to time the main bank after two full cycles of the ringing PI.

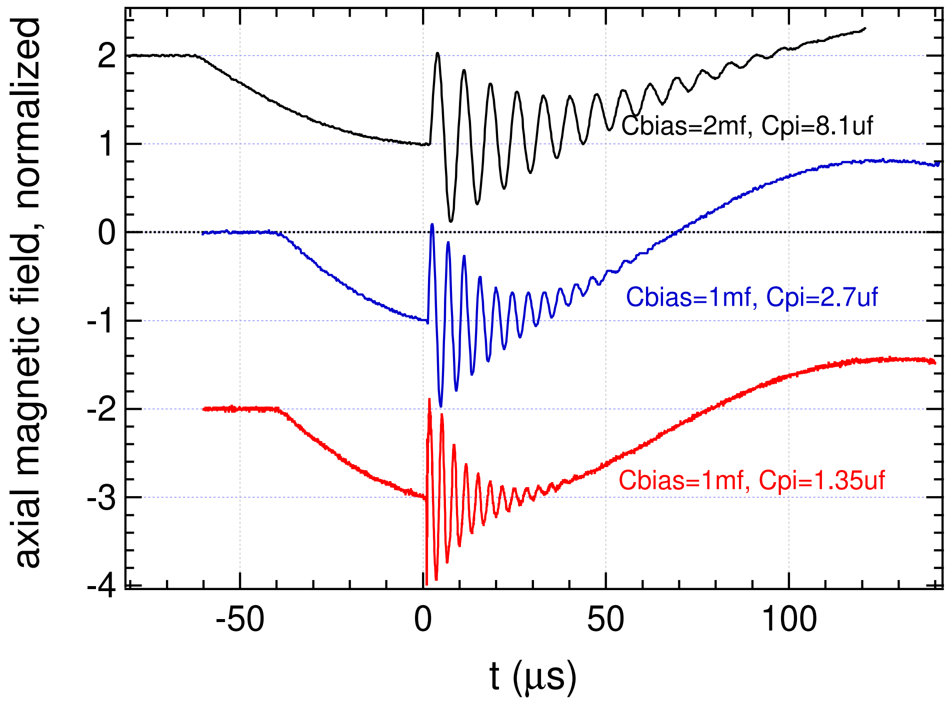
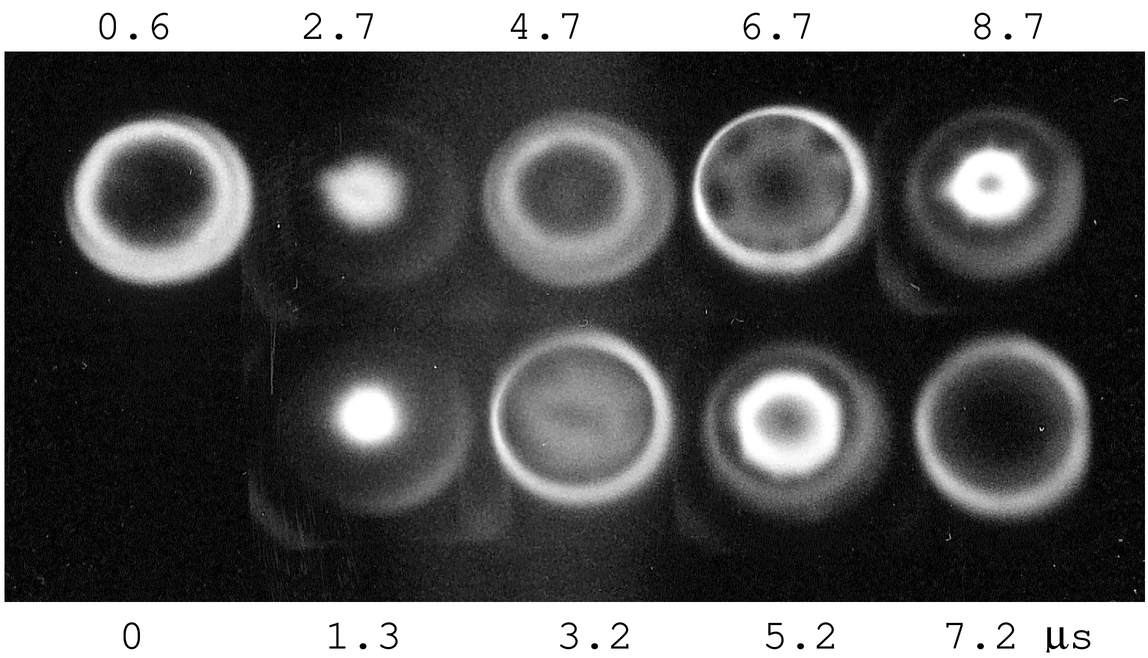


Figure 4: Variation of the Preionization bank ringing frequency as a function of the number of capacitors in the circuit (1, 2, and 6). (The traces are offset for display purposes).

Figure 5: End-on visible light images: Shot 87, P=43 mTorr Hydrogen. 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 spans 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.

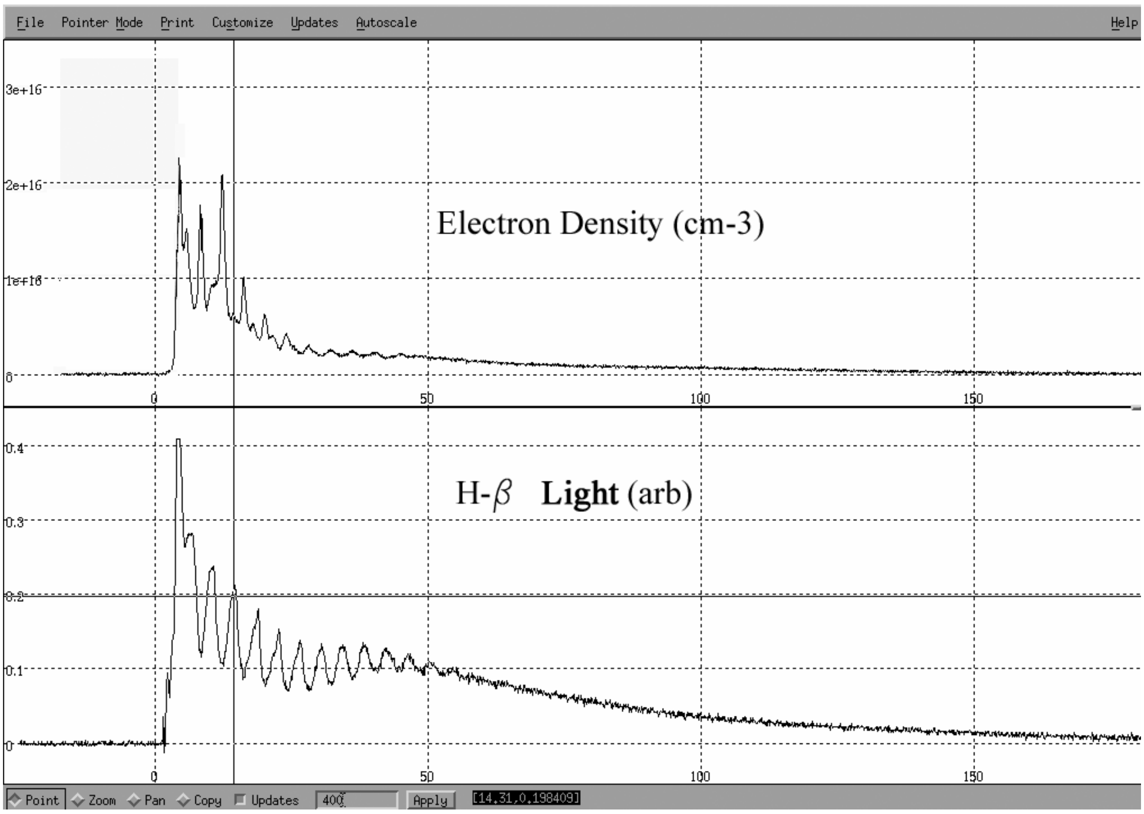


Figure 6: MDS-Plus data of line averaged electron density (assuming 10 cm path length) from the radially viewing 3.39 micron laser interferometer, and a radial view of H-beta light emission using a filtered photomultiplier tube, as a function of time (microseconds) during a 260 mTorr Deuterium PI+Bias 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. The cursor shows that the light and density are out of phase, as seen from these two diagnostics.

Time-resolved Stark broadening of the Balmer series H-beta line of hydrogen, shows similar densities for the brightest light emitting region of the plasma. In Figure 7, the raw line-shape data can be used to also estimate the preionization plasma density, during the 1 microsecond exposure times. It is somewhat higher than the line averaged interferometer measurement, and peaks during times of maximum compression of the ringing plasma. For the highest fill pressure case, the line is becoming optically thick.

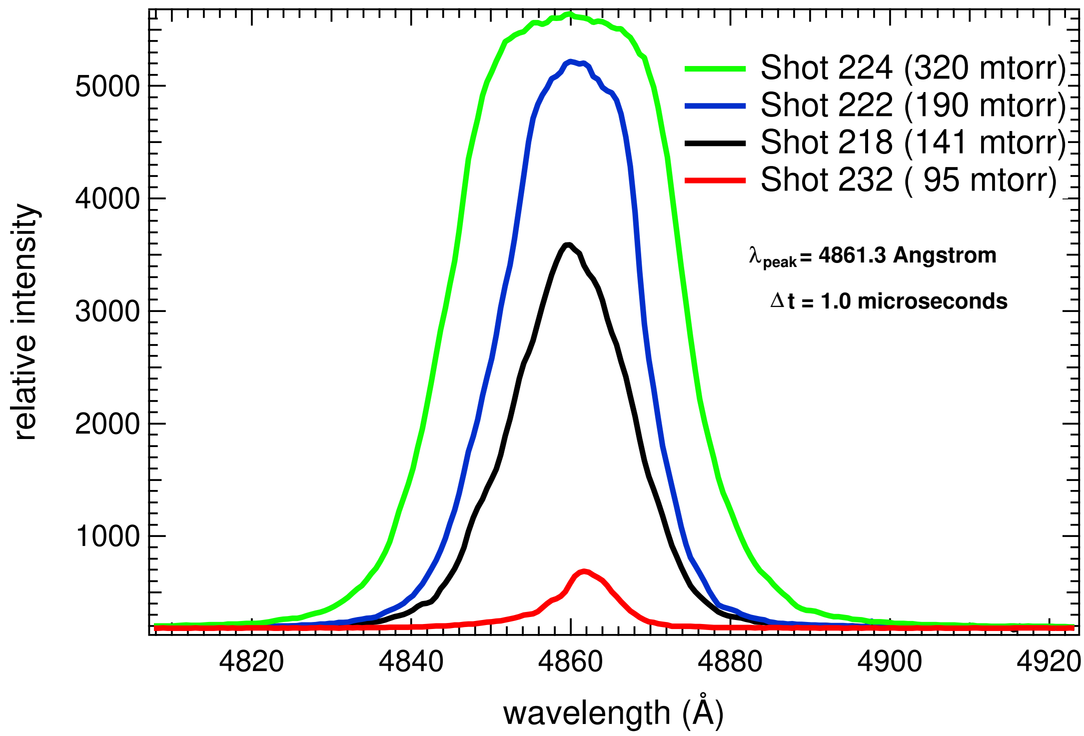


Figure 7: Stark effect line broadening of the H-beta line, as the fill pressure is increased. Exposure of 1 microsecond duration, at a time of 5.9 microseconds after the PI trigger.

From the data in Figure 7, one can use a conversion formula for the observed FWHM linewidth of ~3 nm (for example Eq. 6.4.12 in Hutchinson's book[9]) in order to estimate peak densities of $n_e \sim 6.5 \times 10^{16}$ cm^{-3} for the 320 mTorr case. When we look at old FRX-C data, the ratio of the final FRC line averaged plasma density to the initial preionization line averaged plasma density is in the range of 2-6, so this is certainly adequate for the purpose of forming our MTF target plasma.

4 Future Plans

During the coming year, we anticipate performing FRC studies at high density, 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 diagnostics include multi-chord interferometry, 3-point Thomson scattering, end-on bolometry[10], and end-on x-ray framing imaging. We will vary the fill pressure, bias, and timing while optimizing the plasma lifetime, temperature, and cleanliness, both in the quartz formation region, and in a metal liner. Before any actual integrated plasma/liner implosion experiments are prepared, increased funding levels will be necessary.

5 Acknowledgements

The construction of the machine has also been made possible by the work of William Waganaar, Daniel Begay, Robert Newton, Ed Mignardot, George Sandoval, Gene Linzey, 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.

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