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Abstract. We are testing the first liner implosions of high pressure field-reversed configuration (FRC) plasmas as a physics demonstration of magnetized target fusion (MTF). Integrated hardware on the new Field Reversed Compression and Heating Experiment (FRCHX) at the Air Force Research Laboratory Shiva Star facility, will form initial FRC's at 3 Tesla magnetic field, with high-beta ($\beta \sim 0.9$, $T = \langle T_e + T_i \rangle \geq 300$ eV, $n_e \approx 5 \times 10^{16}$ cm^{-3}) plasma pressures of 20-30 atmospheres, and translate and capture them into an aluminum liner, and then compress them to kilovolt temperatures, forming a high energy density laboratory plasma (HEDLP). Magnetics design and 2-1/2 dimensional MHD fluid (MACH2) simulations for the translated plasma and time-dependent magnetic geometries have been done, construction is nearly finished, and first 1.5 MJ implosion tests are expected in early 2009. Modeling shows that FRC's should be formed after the liner implosion begins, to match plasma lifetime, and the liner compression timescales (~10 and 20 usec, respectively). Details of the hardware, diagnostics, and pre-compression plasma formation and trapping experiments, both from LANL and AFRL, will be presented.

1. Introduction

Los Alamos National Laboratory and the Air Force Research Laboratory (AFRL in Albuquerque, New Mexico) have nearly completed preparations for the first experiment to demonstrate the physics basis of Magnetized Target Fusion (MTF)[1], with the goal of compression of a magnetized target plasma inside a flux conserving shell to heat the plasma to fusion relevant conditions. Since the 2004 IAEA meeting [1], we have converted the FRX-L field reversed configuration (FRC) plasma formation experiment[2] into a translation and capture experiment. At the same time, a new machine at AFRL, based upon FRX-L, called the Field Reversed Compression & Heating Experiment (FRCHX), has been designed, built, and is being tested[3]. It will be mounted under the Shiva Star pulsed power facility, where an aluminum liner will be imploded onto a trapped FRC plasma. Models of the translation, capture, and compression of the FRC are discussed.

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[1] K. F. Schoenberg, R. E. Siemon, et al., http://wsx.lanl.gov/Proposals/mtf_pop_proposal.pdf , " Magnetized Target Fusion: A Proof of Principle Proposal" LA-UR- 98-2413

1.1 Expected Performance

At the simplest level, the experimental design of a translating FRC experiment and its interface to the MTF compression follows from an adiabatic physics model. It invokes general equilibrium and few dynamic assumptions, by presuming that the FRC plasma evolves through a sequence of isentropic magnetohydrodynamic (MHD) equilibria. This thermodynamic approach only accounts for initial and final states and omits dynamics, although a loss factor can be included. In addition, we have modelled the liner and plasma dynamics, using MACH2. For prolate FRC's, elongated equilibria are a reasonable description, and this property enables one to extract two dimensional information from a one dimensional calculation. We consider adiabatic compressions of the idealized cylindrical FRC that can occur either via changes in wall compression or flux compression. A variety of cases have been considered, with radial compression ratios of 10-15*x*. There is a design trade-off between sufficient time for a robust formation process and maximum translation speed to reduce the plasma lifetime requirements. Translation speeds approach the upstream ion acoustic speed, which is ~ 20cm/usec.

	r_s (mm)	E	l_s /2 (m)	Volume (m^3)	Ti (keV)	n (m^-3)	P (bar)	B (Tesla)	Beta	DD neutrons
initial-1	28	6.5	0.18	9.0-04	0.20	3.5E+22	22	2.6	0.83	
final-1	2.8	26	0.072	3.6E-06	4.8	5.3E+24	8.10E+04	160	0.83	3.4E+12
initial-2	28	6.5	0.18	8.7E-04	0.26	1.3E+23	83	5	0.84	
final-2	1.9	33	0.062	1.3E-06	9.1	5.2E+25	1.50E+06	680	0.84	9.2E+14

Table 1. Two design cases are shown above, 40% losses assumed, 0.3 usec dwell time, elongation E= 6.5, 2.4-D compression. Case 1: low field, 10x convergence. Case 2: higher field, with 15x convergence. r_s = separatrix radius, l_s =separatrix length, elongation $E=l_s/2r_s$

2. FRX-L Experiment at LANL

FRX-L [2] is a Field Reversed Configuration plasma experiment at LANL, designed to form, translate, and capture FRC's into an aluminum metal liner, while providing conditions conducive to studying the plasma properties, repetitively, in a controlled laboratory environment.

We have improved the operating parameters of FRX-L plasmas [4-7]. An increased sustained main bank magnetic field was enabled by successful implementation of a lower ripple crowbar switch. We designed and built improvements to the pulsed power hardware, including an AFRL redesign for the crowbar switch and cable header on the main bank. This dramatically reduces both the modulation of the Θ-coil current and the resultant FRC decompression and recompression that appears after the crowbar switch is triggered. The "ideal" crowbar circuit has zero switch inductance and no shared volume between the source loop and the load loop, as this represents a mutual inductance or coupling between the two loops. The previous crowbar switch had significantly more mutual inductance (~25nH) than new crowbar switch (< 4nH) between the main bank-to-crowbar and crowbar-to-Θ coil loops, which induced a voltage upon the crowbar-to-Θ-coil loop, and thus the observed modulation on the Θ-coil current. The plot of the Θ-coil magnetic field in Fig. 1 shows the improved performance of the new crowbar switch. Because of the low inductance and isolation between all 4 rail-gap switch segments, it is difficult get all the railgaps to fire consistently. This will become far less of an issue once the FRC translates out of the theta coil region before the crowbar fires. Data with improved crowbar operation, as shown in Fig. 2, exhibit increased trapped flux, density, and temperature. The 2-3 MPa (20-30 Atm) plasma pressure corresponding to this shot is substantial, , i.e., a β~ 1confinement pressure exerted by a 2-3 T magnetic field.

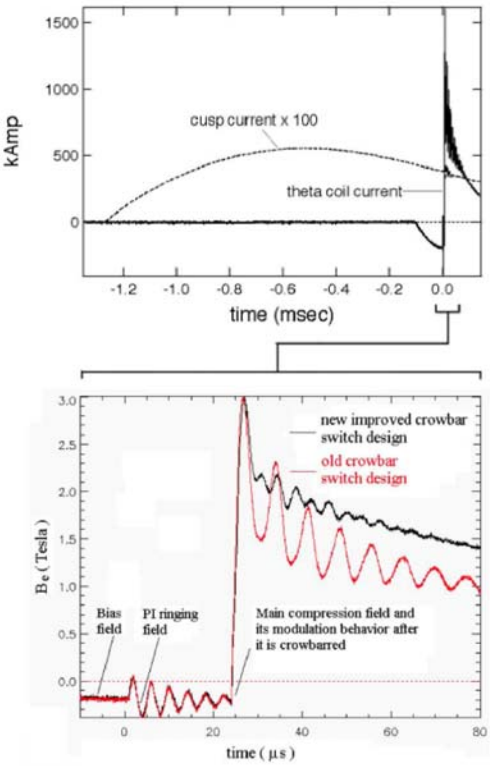

Figure 1: (upper) Long time scale current in the Θ and cusp/mirror coils. The cusp current creates a B_Z opposite to the initial bias B-field. In this case the main bank fires at t = 25 μs and rings while the crowbar forces the current to monotonically decay with its L/R time. (lower) Waveforms from one of the magnetic probes (located on the top of Θ -coil segment B) recorded during a shot with the old crowbar switch (red) and with the new crowbar switch (black).

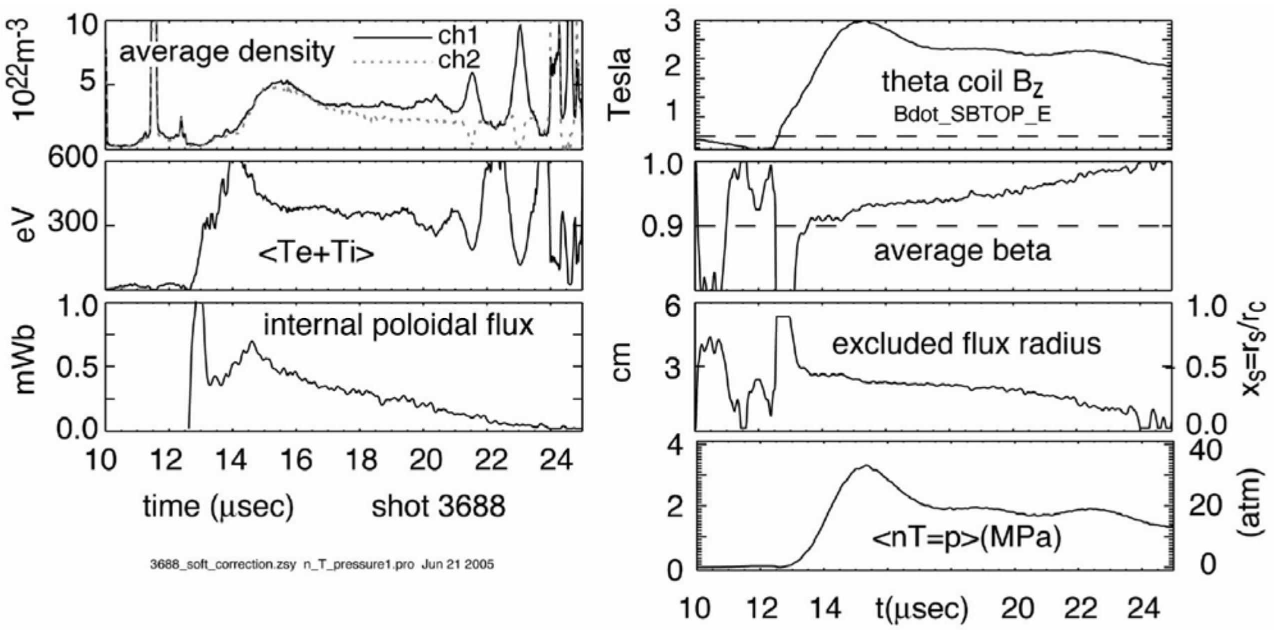

Figure 2: High pressure FRC parameters in FRX-L, following installation of improved high-current crowbar system. The plasma pressure is 2-3 MegaPascals, or 20-30 bars; higher than even the largest tokamak plasmas. An n=2 rotational instability develops by t=20 μsec.

In FY2008 we have begun operating FRX-L again, after installation of conical-Θ coils, and addition of fast cusp coils, a translation and mirror bank, and tripling the size of the bias bank. The FRC plasma is observed to translate at ~15 cm/μsec, as predicted [8]. The conical theta coil offers the simplest scheme for FRC formation, and the translation during formation has the additional advantage of forcing reconnection during formation. The cone angle is expected to add toroidal magnetic field, good curvature to FRC magnetic field lines, and helicity [8] which is also expected to add robustness to the stability [9].

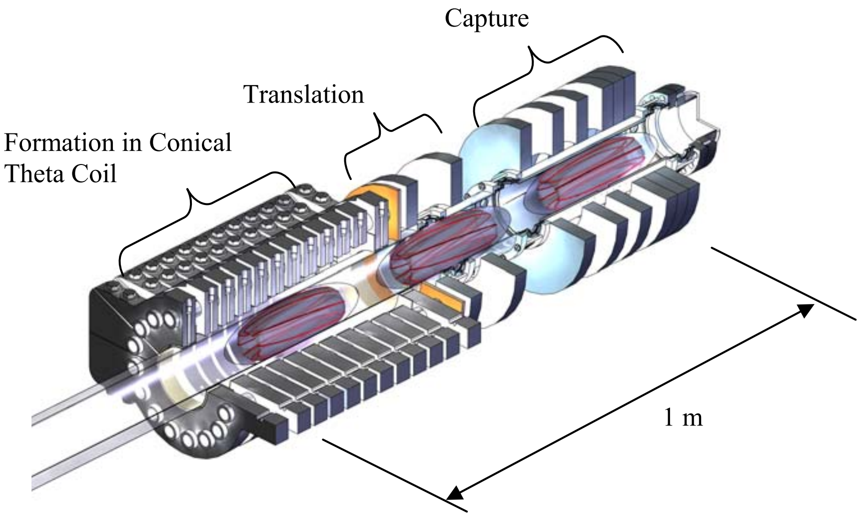

Figure 3: FRCHX at AFRL and FRX-L at Los Alamos use an identical conical theta coil set to form a translating FRC, and guide and capture it in a liner compression region. The Shiva Star capacitor bank will couple ~1.5 MJ into the kinetic energy of the aluminum liner, which collapses cylindrically at ~ 5km/sec. Initially, expected neutron yields are in the range of > 10^{12} DD neutrons per shot, at a density of ~ 5×10^{18} cm^{-3}, and temperature of ~ 5 keV.

3. FRCHX Experiment at AFRL

The Field Reversed Compression and Heating Experiment, FRCHX, is a new FRC machine at the Air Force Research Laboratory in Albuquerque, based on FRX-L. It is designed for vertical orientation, and to fit underneath the Shiva Star capacitor bank. Shiva Star will compress an aluminum liner, and the FRC plasma, in the capture region.

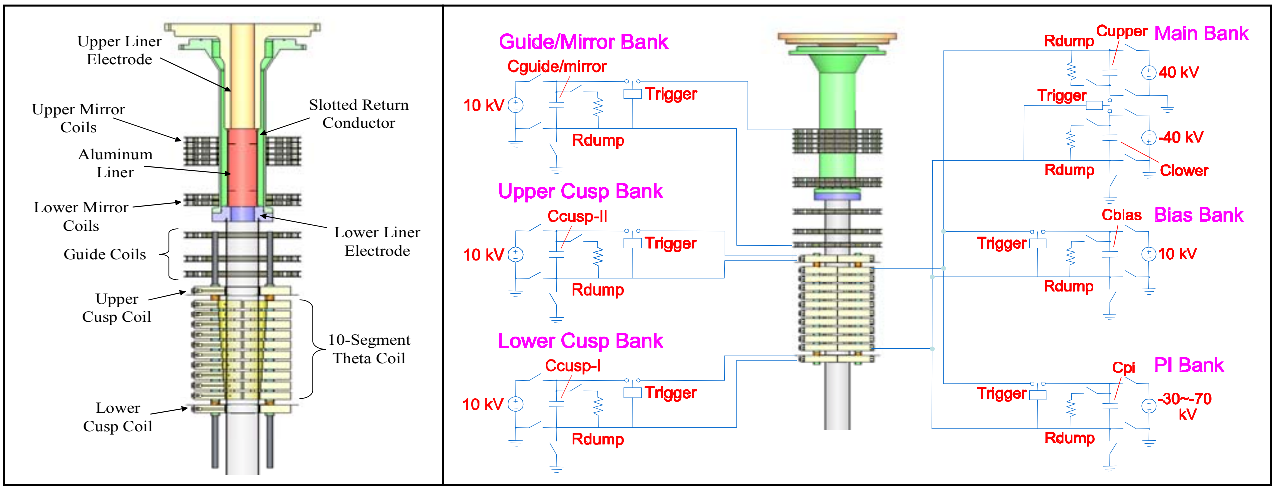

Figure 4: The FRCHX machine stack is oriented vertically, to fit underneath the 9 MJ Shiva Star liner-driver capacitor bank. Six different capacitor banks make up the FRC plasma injector power systems.

As shown in Fig. 4, FRCHX uses three independent capacitor banks in the FRC formation process: a Bias bank, consisting of two 10 kV, 2.5mF bank modules, a Preionization bank, consisting of a single 100-kV, 2.1 μF capacitor, and a Main bank, which is essentially a Shiva Star bank module (144 μF, 60 kV). Though independently charged and triggered, these three banks all drive the same single-turn Θ-coil. Two additional banks drive fast Cusp coils at each end of the Θ-coil, which are used to aid with magnetic reconnection during the final stages of the formation process. Each of these Cusp banks consist of three 10-kV, 500 μF capacitors. The Guide/Mirror bank (10-kV, 12 mF, 0.6 MJ) drives "slow" multi-turn translation and mirror coils connected electrically in series, with an overall 7 millisecond ¼ -cycle rise time. Fields from this bank must soak through a slotted return feed and the aluminum liner itself, prior to the arrival of the plasma.

The FRC plasma is automatically ejected by JxB forces, caused by conical Θ-coils, whose cone angle is variable between 0º and 6º. For initial tests use 4º. As the FRC exits from the Θ and Upper Cusp coils, a Guide field set up by three multi-turn coils allows the FRC radius to expand to 3-4 cm. The FRC then passes through a minor magnetic mirror and an 8 cm diameter aperture in the lower liner electrode to enter the solid liner region. A magnetic mirror at the upper end of the liner stops the FRC's forward motion, and since part of its kinetic energy is converted into internal thermal energy in this process, it lacks the momentum needed to exit the liner region again through the minor mirror.

Nondestructive testing of systems and plasma formation/capture are underway, and imploding plasma/liner tests at a shot rate of 3-5 per year are beginning in early 2009. An engineering test shot of magnetic field soak-through, and magnetic flux compression, is scheduled for November 2008. A new four-chord interferometer has been built to diagnose the plasma density before it arrives in the aluminum liner. Filtered visible light fibers will watch the plasma from the formation through the translation region. End-on XUV spectroscopy, soft x-ray imaging (or filtered PIN diodes), and a variety of neutron diagnostics are planned for plasma implosion shots.

4). Modeling of plasma translation and implosion

We have used a variety of modelling codes, to design the FRC experiment, especially MOQUI [10] and the 2½-dimensional MACH2 [11]. MOQUI is useful for translation simulations, runs quickly, and has been benchmarked against FRC experiments.

Frames from a MOQUI simulation are shown in Figure 5. They start with formation in the conical Θ-coil at t=0 μs with a 3.5 Tesla main field, acceleration by t = 2 μs, expulsion at t = 4.5 μs, and translation by t = 6.5 μs through a guide field region, after which it collides with a 2.7 Tesla mirror field on the right hand side. A subsequent bounce leads to leftward motion at t=11 μs and final stagnation and dissipation are shown after t = 21 μs. The expected translation speed is ~15 cm/μs (which asymptotes to the source ion acoustic speed), and the elapsed time of 21 μsec is consistent with demonstrated liner implosion times of 22 μsec [1]. A movie can be viewed on the web, at http://wsx.lanl.gov/moqui.htm

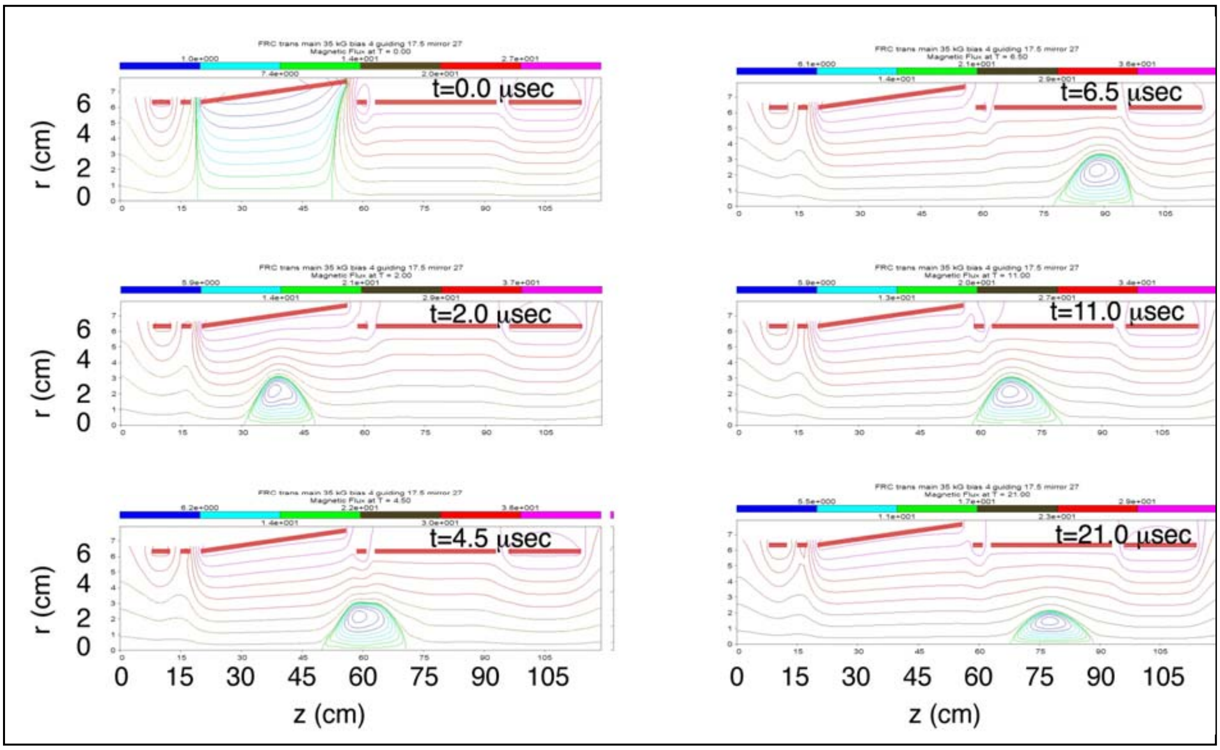

Figure 5: Six frames of a MOQUI code simulation for typical experimental parameters and the planned conical Θ-coil design for FRC translation experiments. The expected liner implosion time will be ~22 µsec, so one timing option is to begin the liner implosion first, before forming and injecting the FRC on Shiva Star.

On the other hand, MACH2 can perform integrated MHD simulations of the complete experiment including formation and translation of the FRC plasma and its capture and compression by an imploding liner. We use the Chodura resistivity initially, and switch to classical resistivity after the FRC is formed. Liner portions of the simulation have already been benchmarked against experiments. The simulation is particularly useful to guide the design of mirror fields in the capture region, which are dynamically compressed even as the FRC first arrives in the liner.

Results from one such simulation shown on the next page in Fig. 6, start 7.3 µs after the liner bank fires and 4.7 µs after main FRC bank fires, as the FRC is about to be expelled from the formation region. During the following microsecond, the FRC translates 25 cm along a guide field toward the liner where it is captured by mirror fields at both ends of the liner. The design values of those mirror fields, 2 T at the near end and 3 T at the far end when insertion and capture begins at 8.5 µs, are roughly 20% higher than their initial values at this stage of compression by the liner. As seen at 16 µs, they are 6 T and 9 T, respectively; the field around the FRC is about 9 T and the peak density of the FRC is $2.8\times10^{17}/cm^3$.

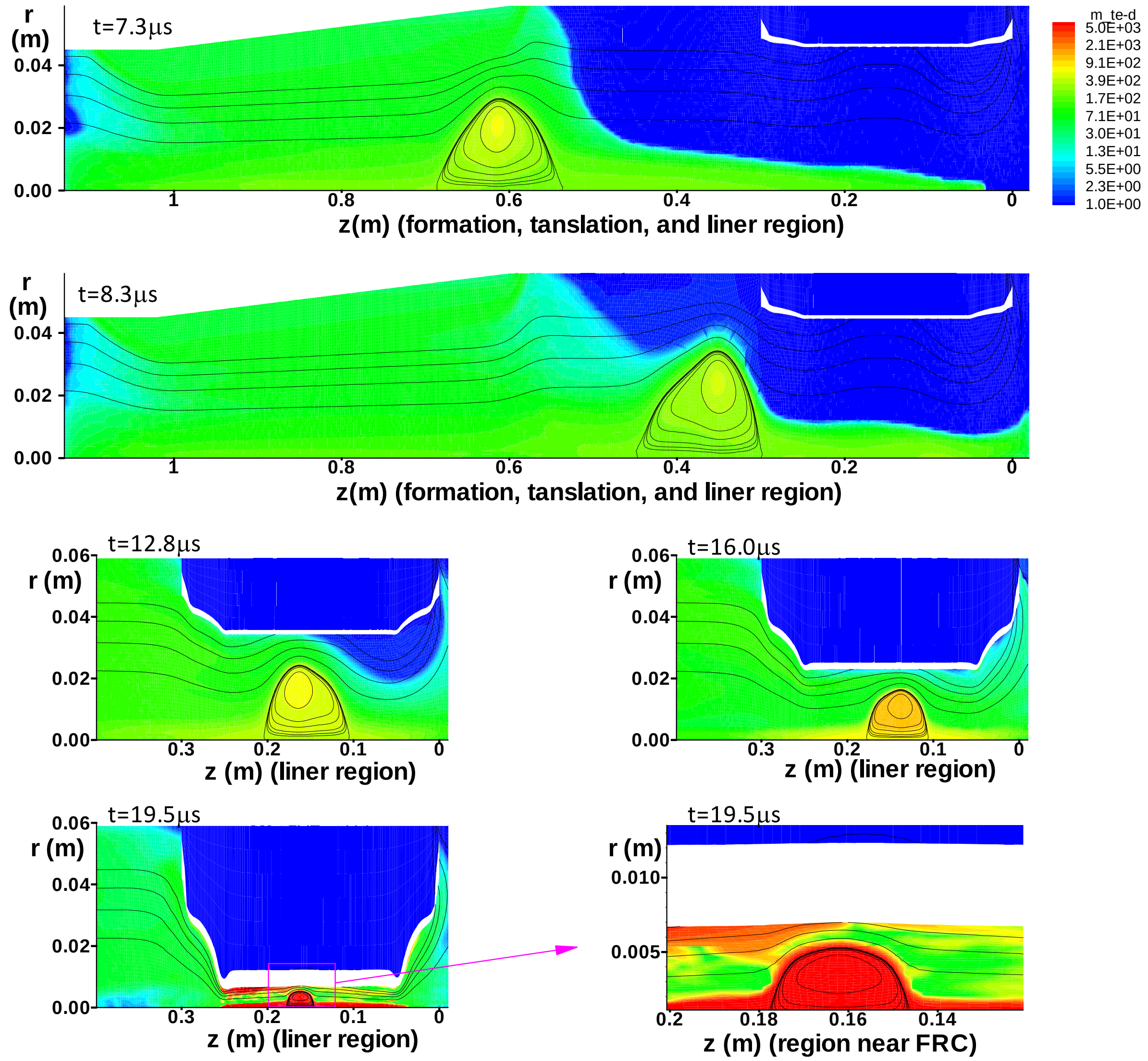

Figure 6: Temperature and flux contours at five times from a MACH2 simulation with typical experimental parameters for the planned conical FRC formation, translation, and liner compression experiments. The white region in each of the images is the imploding liner. The last four images omit the formation and most of the translation region. All times are relative to the beginning of the liner bank firing.

We see a modest loss of particles as the FRC bounces off the final mirror before it settles down in the liner region. These simulations use a quasi-Lagrangian grid in the liner and an adaptive quasi-Eulerian grid in the rest of the problem so that the radial and axial resolutions in the FRC are both roughly three times smaller than the respective average cell sizes of 1 mm and 2 mm. The requirement to model high field, low density regions limits the time step so that hundreds of thousands of time steps are necessary; thus, complete simulations through compression take a few days in parallel on a dual core 3 GHz 64-bit processor with optimized in-memory MPI communications. The elliptic vacuum field problem limits efficient parallelization, and inter-processor communication is slower than intra-processor, so that though the dual-core run is 80% faster than a serial run, a two-processor four-core run is not much faster. Movies of this MACH2 simulation can be viewed on the web at http://wsx.lanl.gov/mach2.htm.

5. Summary

FRCHX is in final assembly, and individual pulsed power systems are being tested, in preparation for the first solid liner compression experiments on a high-density field reversed configuration plasma to multi-keV fusion conditions. Modeling has been used to guide the design of the experiment, and soon we will compare with actual data.

6. References

[1] G. A. Wurden, T. P. Intrator, S. Y. Zhang, I. G. Furno, S. C. Hsu, J. Y. Park, R. Kirkpatrick 1), R. M. Renneke, K. F. Schoenberg, M. J. Taccetti, M. G. Tuszewski, W. J. Waganaar, Zhehui Wang, R. E. Siemon, J. H. Degnan, D. G. Gale, C. Grabowski, E. L. Ruden, W. Sommars, M. H. Frese, S. Coffey, G. Craddock, S. D. Frese, N. F. Roderick, "FRC plasma studies on the FRX-L plasma injector for Magnetized Target Fusion", 20th IAEA Fusion Energy Conference, Nov. 1-6, 2004, Vilamoura, Portugal. IAEA-CN-116/IC/P6-53

[2] J. M. Taccetti, T. P. Intrator, G. A. Wurden, S. Y. Zhang, et al., "FRX-L: A Field Reversed Configuration Plasma Injector for Magnetized Target Fusion". Rev. Sci. Instruments, **74**(10), 4314 (2003).

[3] J. H. Degnan, D. J. Amdahl, A. Brown, T. Cavazos, et al., "Experimental and Computational Progress on Liner Implosions for Compression of FRC's", IEEE Transactions on Plasma Science, **36**, pg. 80-91 [2008].

[4] Shouyin Zhang, T. P. Intrator, G. A. Wurden, W. J. Waganaar, J. M. Taccetti, and R. Renneke, C. Grabowski, E. L. Ruden, "Confinement analyses of the high-density field-reversed configuration plasma in the field-reversed configuration experiment with liner", Physics of Plasmas **12**, 052513 (2005).

[5] E. L. Ruden, Shouyin Zhang, T. P. Intrator, and G. A. Wurden, "Experimental profile evolution of a high-density field-reversed configuration", Physics of Plasmas, 13, 122505 (2006).

[6] T. Intrator, S. Y. Zhang, J. H. Degnan, I. Furno, C. Grabowski, S. C. Hsu, E. L. Ruden, P. G. Sanchez, J. M. Taccetti, M. Tuszewski, W. J. Waganaar, and G.A. Wurden, "A high density field reversed configuration (FRC) target for magnetized target fusion: First internal profile measurements of a high density FRC", Physics of Plasmas **11**(5), 2580, (2004).

[7] T. P. Intrator, Jaeyoung Park, James H. Degnan, I. Furno, Chris Grabowski, S. C. Hsu, Edward L. Ruden, P. G. Sanchez, J. Martin Taccetti, M. Tuszewski, W. J. Waganaar, Glen A. Wurden, Shouyin Y. Zhang, and Zhehui Wang, "A High-Density Field Reversed Configuration Plasma for Magnetized Target Fusion", IEEE Trans. on Plasma Science, **32**(1), 152 (2004).

[8] T. P. Intrator, R. E. Siemon, P. E. Sieck, "Adiabatic model and design of a translating field reversed configuration", Phys. Plasmas, **15,** 042505 (2008).

[9] H. Y. Guo, A. L. Hoffman, L. C. Steinhauer, and K. E. Miller, "Observations of Improved Stability and Confinement in Spherical-Torus-Like Field Reversed Configuration", Phys. Rev. Lett., 95, 175001 (2005).

[10] R.D. Milroy and J.U. Brackbill, Phys. Fluids **25**, 775 (1982).

[11] R. E. Peterkin, Jr., M. H. Frese, and C. R. Sovinec, "Transport of Magnetic Flux in an Arbitrary Coordinate ALE Code," J. Comp. Phys. **140**, 148 (Feb. 1998).