Magnetized Target Fusion Research Results and Plans

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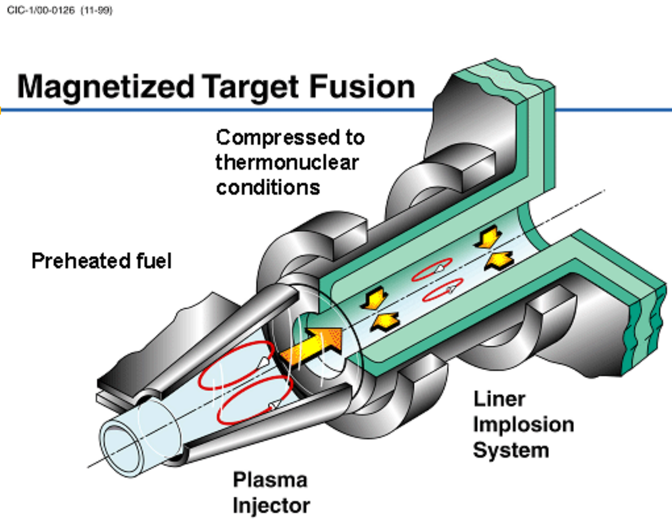
Fusion: Pathways to the Future

Fusion Power Associates Annual Symposium

What is Magnetized Target Fusion?

- A method to make fusion energy, using a combination of magnetic and inertial techniques
- A way to heat and compress a starting (target) plasma to high temperature, density, and magnetic field, resulting in significant fusion gain
- Operates at ~ 1Megabar pressures (or higher). A High Energy Density Physics approach to fusion.
- Combines knowledge of compact toroid plasmas (from OFES), with liner implosion technology (from DOD & NNSA)
- MTF is intrinsically a pulsed approach to fusion

Magnetized Target Fusion (FRC):



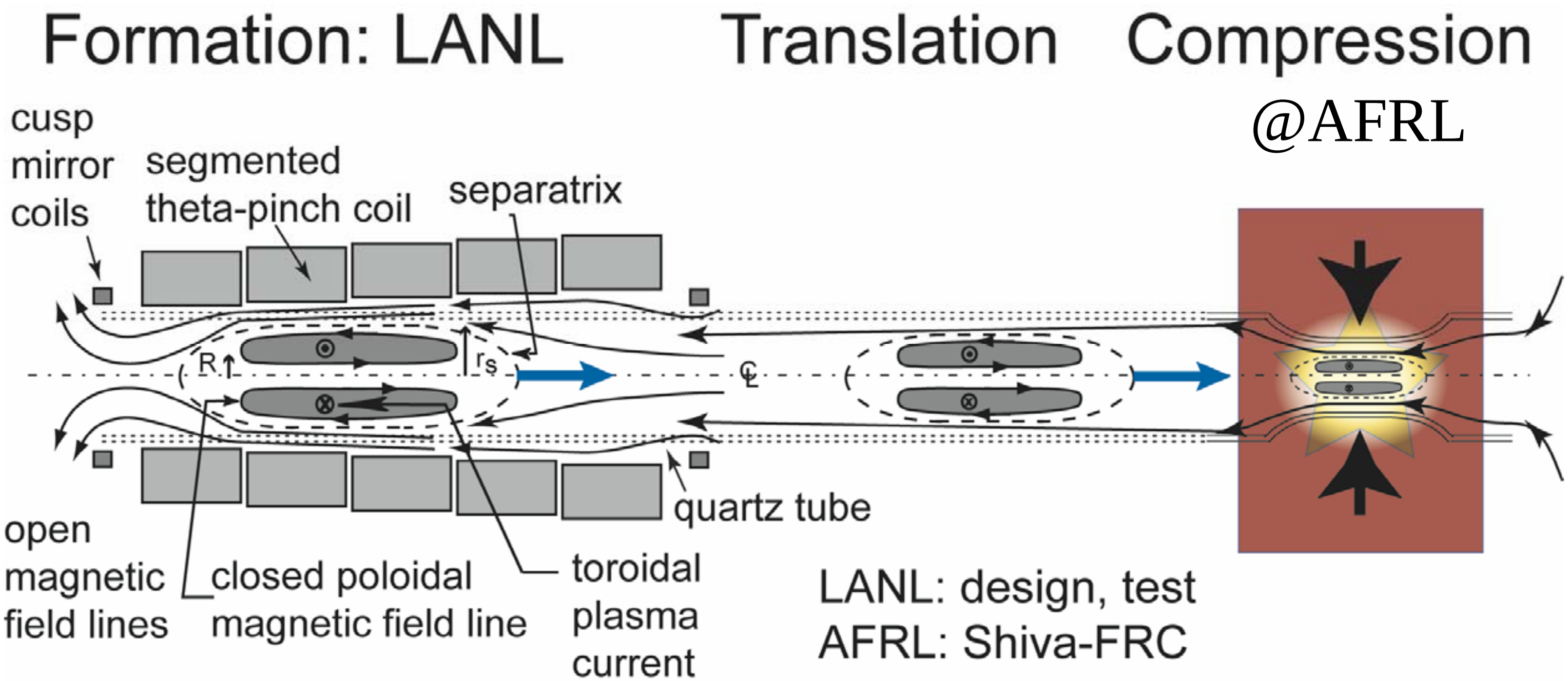
This is a fusion concept where:

- The plasma beta ranges from 0.8 to 1
- The heart of the device fits on a modest table-top
- The plasma density is high ~10^{19} cm^{-3}
- The current density can be 1000 MA/m^2
- The magnetic field confining the plasma is 500 Tesla !
- The auxiliary heating power level is ~ 1000 Gigawatts !
- HEDP achieved by "slow" adiabatic compression (to ~1 MBar)
- Research can be conducted with existing facilities and technologies
- In a reactor, on each pulse the liquid first wall would be fresh
- The repetition rate would be ~0.1 Hertz, so that there is time to clear the chamber from the previous event

Magnetized Target Fusion: pathway & research elements

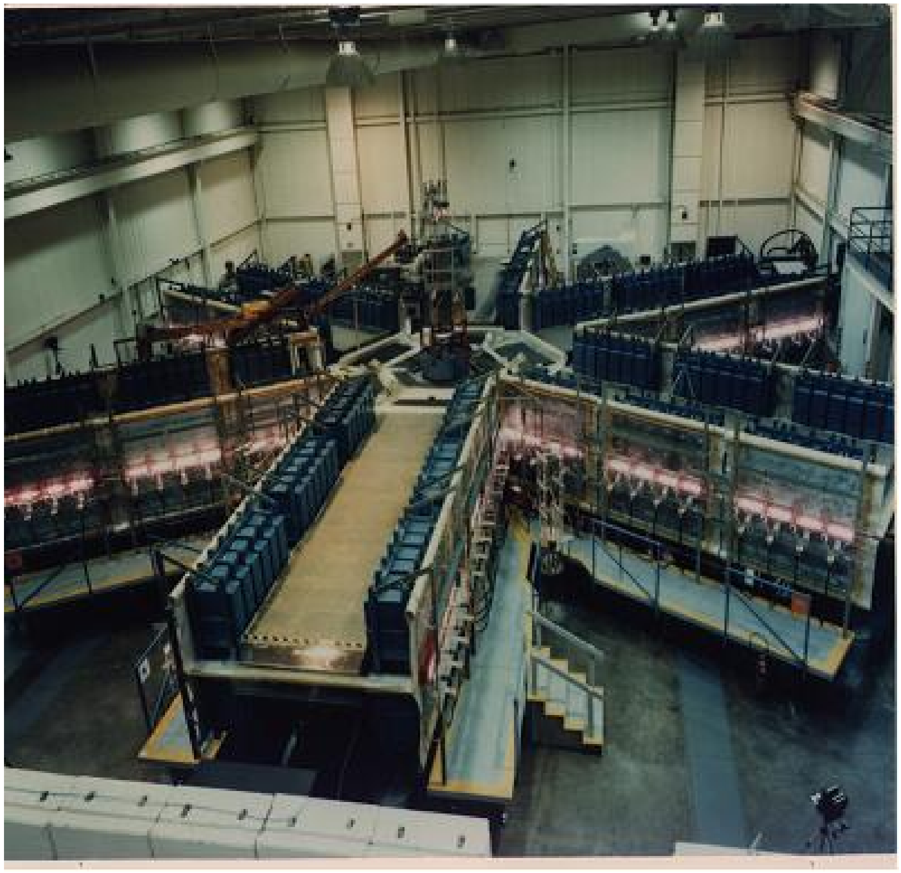
- Target plasma (**FRX-L**) FRC development at LANL
  - Intrator, Wurden, Hsu, Dorf, technicians & students
  - FRC physics collaborations with U of Washington
- Liner compression facility (**Shiva Star**) at AFRL
  - Jim Degnan, Chris Grabowski, Ed Ruden, & engineering support
- FRC hybrid/MHD and 3D fluid modeling
  - Elena Belova, Mike & Sherry Frese (*NumerEx*), Dick Siemon, and students
- Forward-looking technologies
  - Doug Witherspoon, (*HyperV Technology*) plasma guns
- Reactor scenarios
  - Ron Miller (*Decysive Systems*), Ron Kirkpatrick

Magnetized Target Fusion, liner compression of FRC, physics test



- Pulsed, high pressure approach to fusion
- Inertial + magnetic confinement
- Multi-keV fusion grade plasma

Shiva Star Facility at AFRL



Parameters for magnetic pressure implosions of cylindrical or spherical metal shells (solid liners)

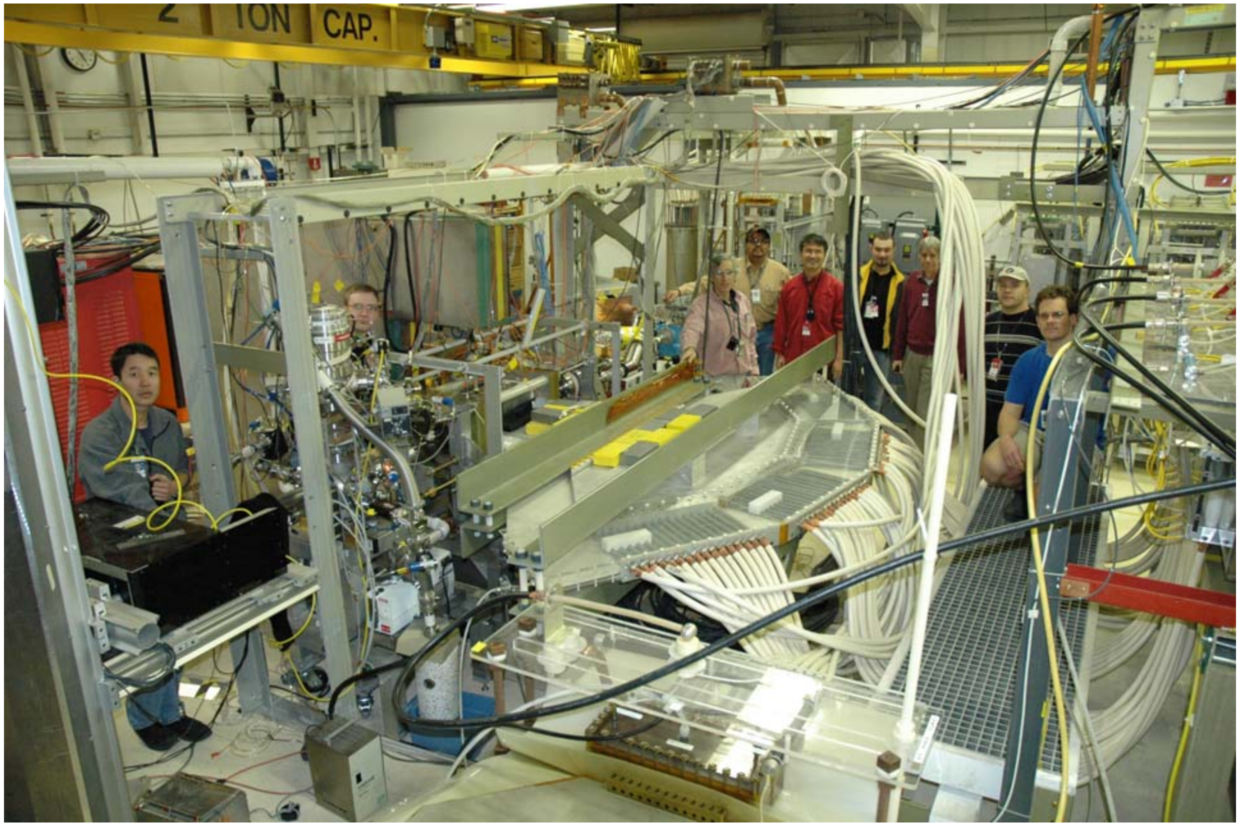
- **80 to 90 kV, 1300 uF, 25 to 45 nH**
- **11 to 16 Megamp, ~10 μsec risetime discharge implodes 10 cm diameter, 1 mm thick, 4 to 30 cm long Al liner in 15 to 24 μsec**
- **e.g., 4.4 MJ energy storage gives 1.5 MJ in liner KE**

Shiva Star Capacitor Bank (up to 9 Megajoules, 3 μsec) used for implosion - compression experiments

LANL's FRX-L Field Reversed Configuration (FRC) for target plasma development

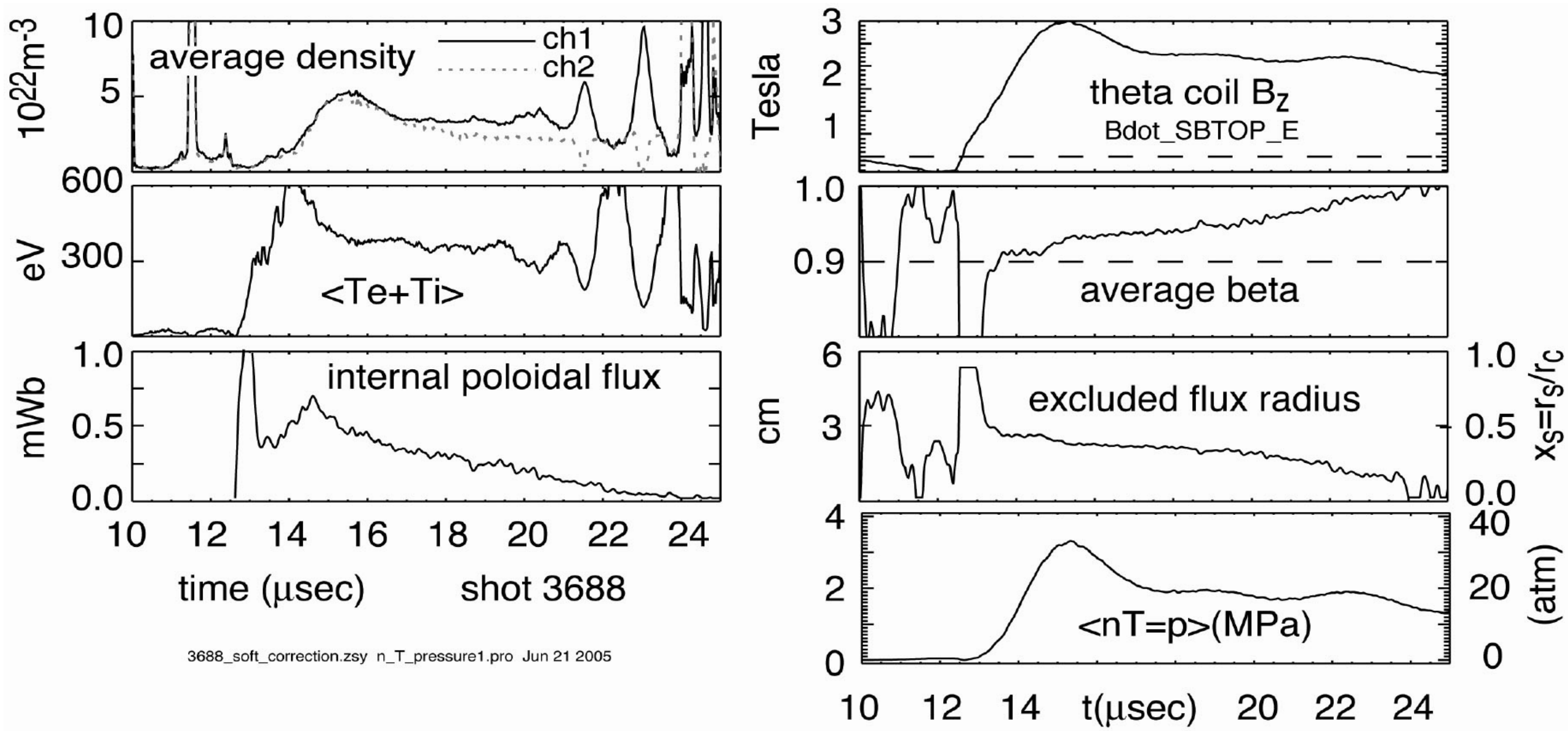
Project/Concept Description: Magnetized Target Fusion. Develop a suitable plasma injector using a high density FRC

GOAL: To make the first physics demonstration of MTF by imploding a field reversed configuration plasma with a metal liner



- The FRX-L experiment and team

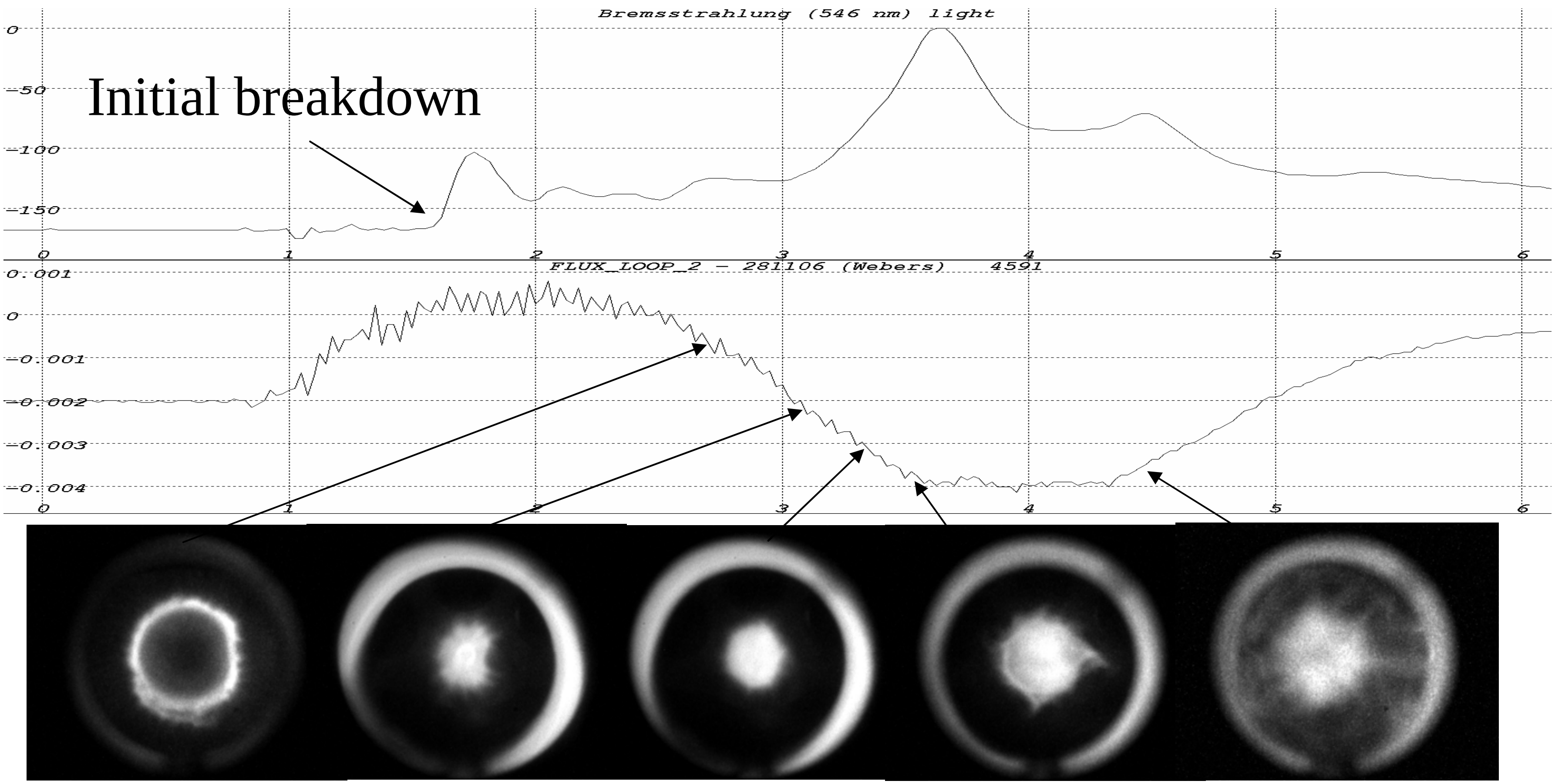
High pressure FRC plasmas are produced in FRX-L



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

We start with a ringing theta-pinch "PI" plasma on FRX-L

When is the best time to form the FRC?



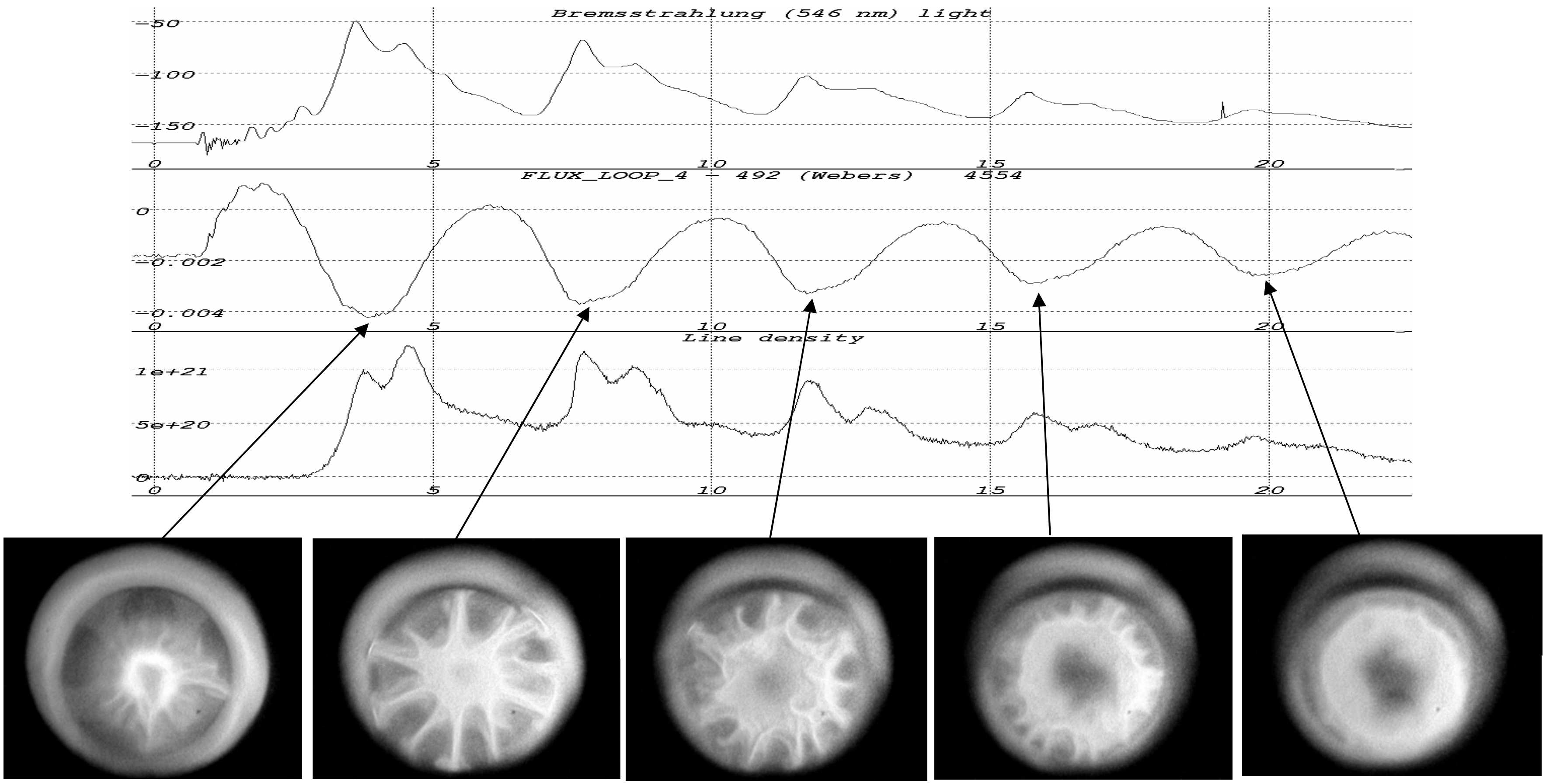
2.7 usec 3.1 usec 3.3 usec 3.5 usec 4.6 usec

End-on view, 40 nsec exposures, 1280x1024 images, first ringing cycle

Studying details of the PI plasma on FRX-L:

Fluting occurs during each expansion phase, decreasing at later times

==> more symmetric seed plasma is available to form the FRC

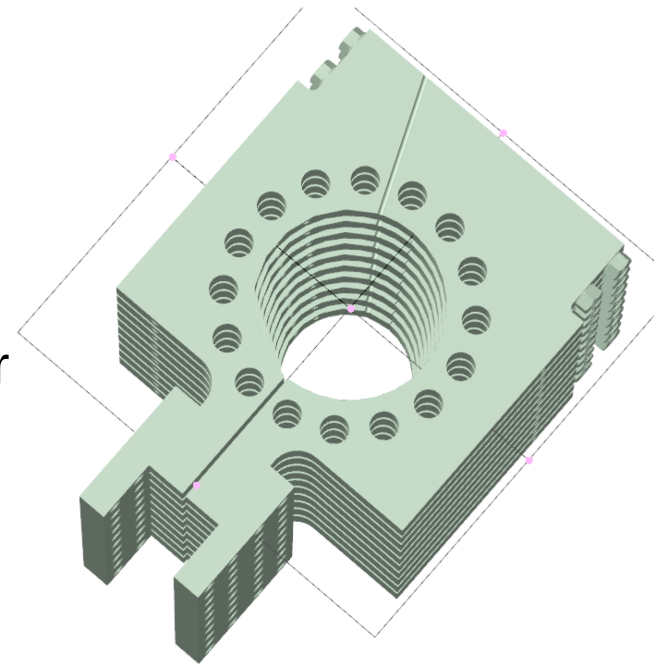


3.9 usec | 7.9 usec | 11.9 usec | 15.9 usec | 19.8 usec

White light, 100 nsec exposures

Construction of the combined plasma/liner experiment at AFRL has begun

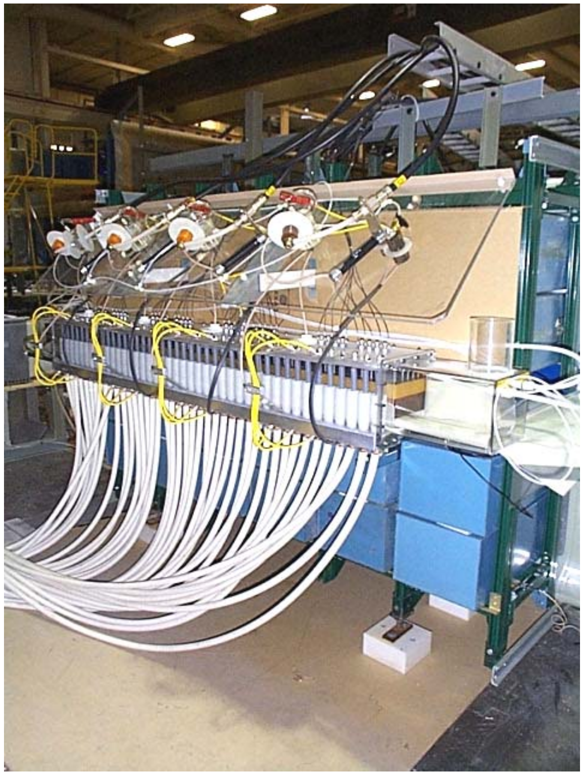
- Modular theta coils for translation are in the shop being fabricated
- Completed assembly of main bank and crowbar switch for the new FRC at AFRL.
- Completed design, fabrication, and assembly of compact theta coil cable header. (A compact design was needed for placement under the Shiva bank.)
- Began pulsed power tests with the main bank and crowbar switch at AFRL.
- Developed slotted bus work design to provide inductive isolation between individual rail gaps in FRX-L crowbar switch.



A new Main Bank and Crowbar Switch for the FRC plasma injector at AFRL has been built, and is being tested

Front view of the Main bank with fiberglass cable trays above to bring the Main bank and Crowbar switch trigger cables over from the trigger units.

Back view of the Main bank showing the Crowbar switch and the RG 17/14 transmission line cables to run to the Theta-coil-cable header.



A Compact Theta Coil Cable Header (different than FRX-L's) has been designed and built

Solid Works® rendering of the Theta coil cable header design. The red cables in the header represent the PI bank cables, the blue cables are for the Bias bank, and the green cables are Main bank cables.

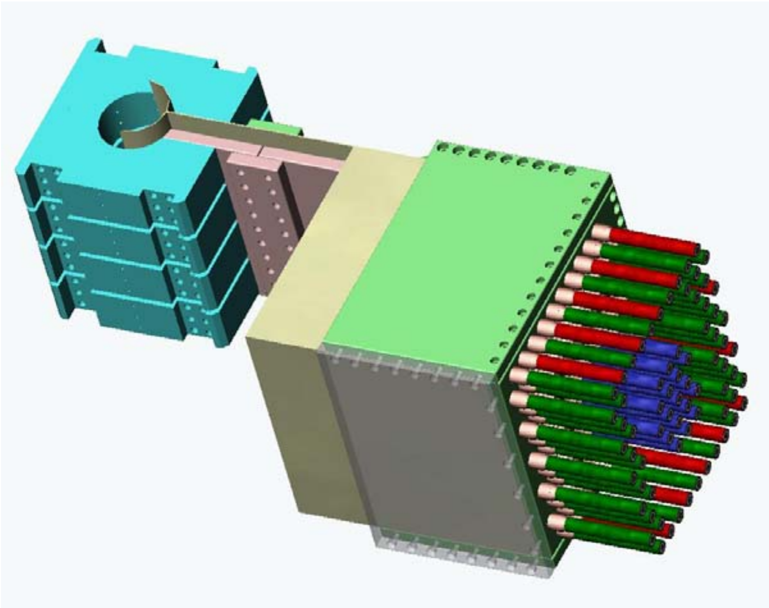
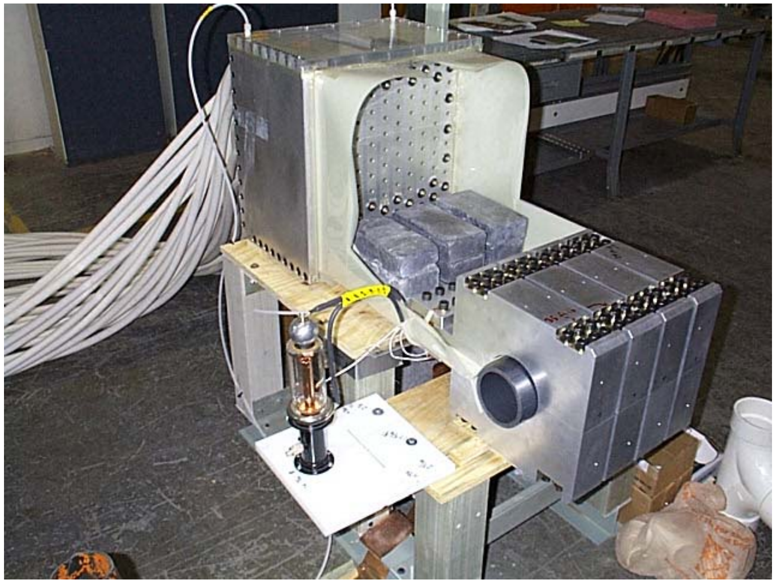
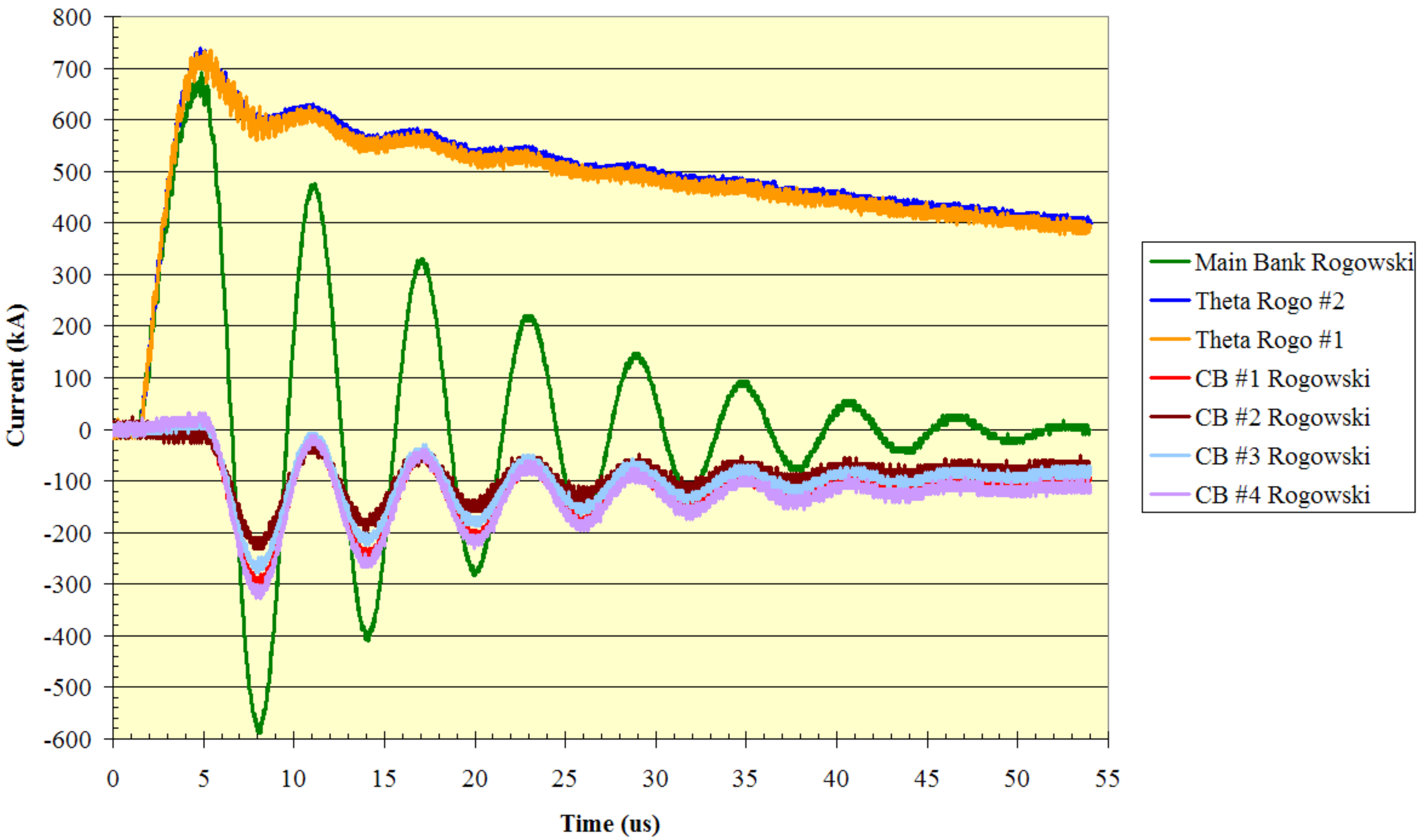


Photo of the finished Theta coil load and cable header setup. The assembly has been placed on a temporary wooden and fiberglass stand for initial tests.



Pulsed Power Testing of new hardware at AFRL

Current waveforms recorded during Test Shot 13. All four Crowbar rail gaps conducted current during this test shot and shared current fairly uniformly.

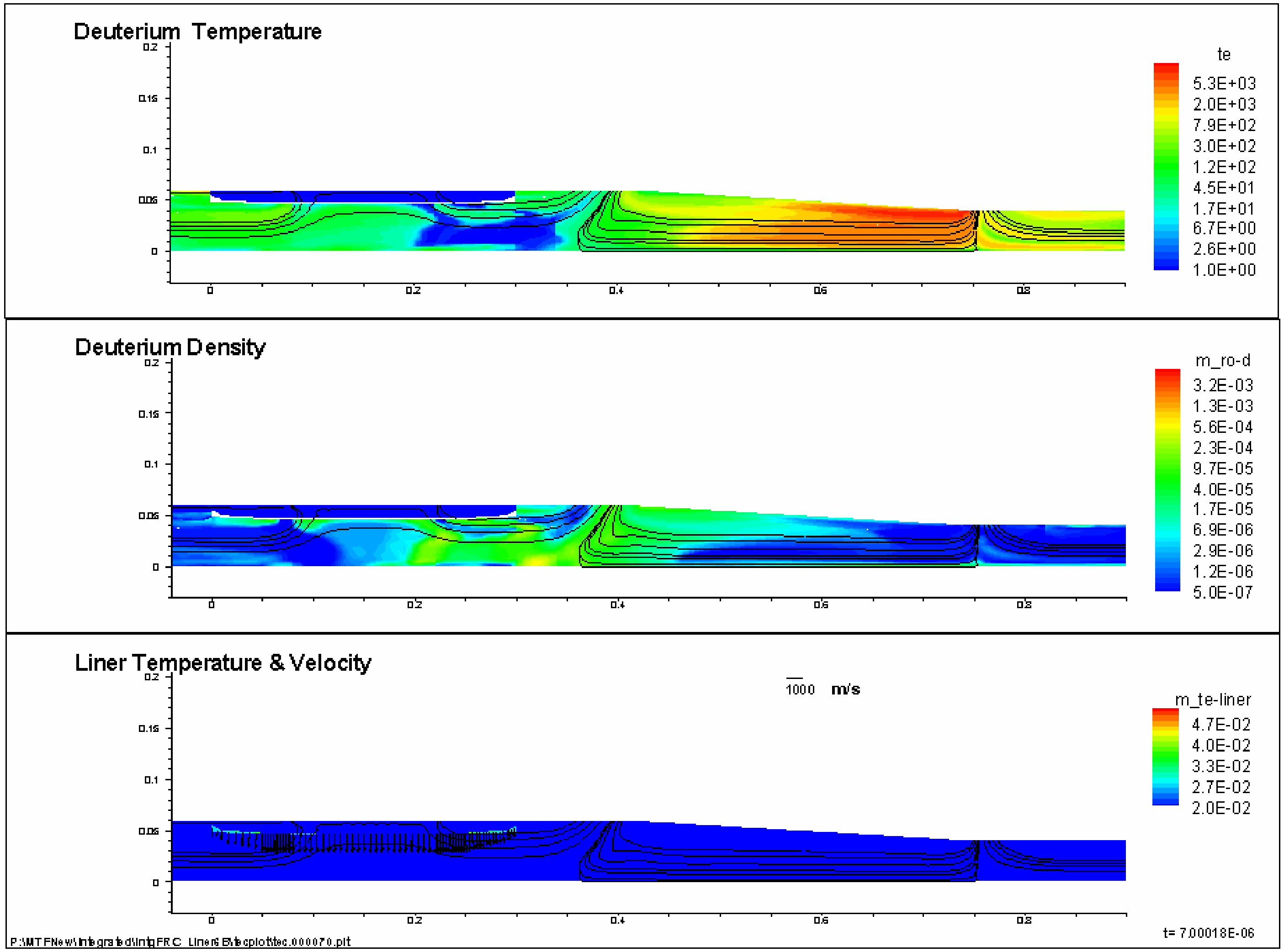


MACH2 Integrated Simulation Shows Formation, Translation into the Imploding liner, and Compression of the FRC

NumerEx

- Preliminary runs
- Several iterations to adjust the mirror fields and the regions over which they were applied, before an FRC was captured.
- The first attempts rebounded off the first mirror field or off the second one and all the way back out.
- In this example, the FRC splits because the magnetic bottle is too short.

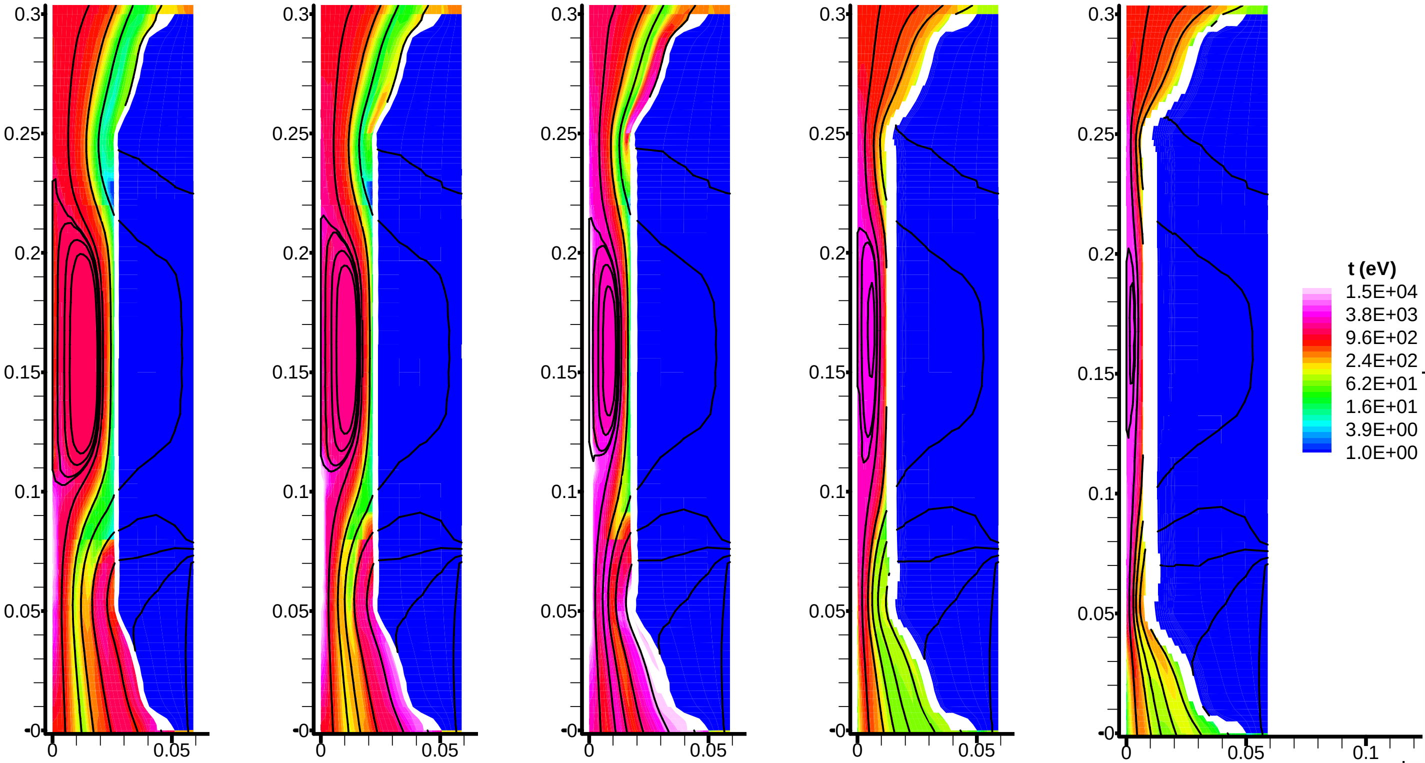
This balancing act shows why early simulation is important to the design of the experiment.



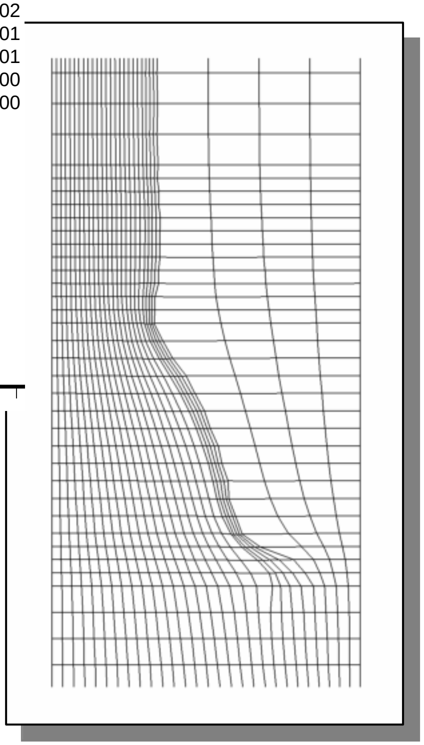
Movie

Liner Compression of an FRC plasma

NumerEx



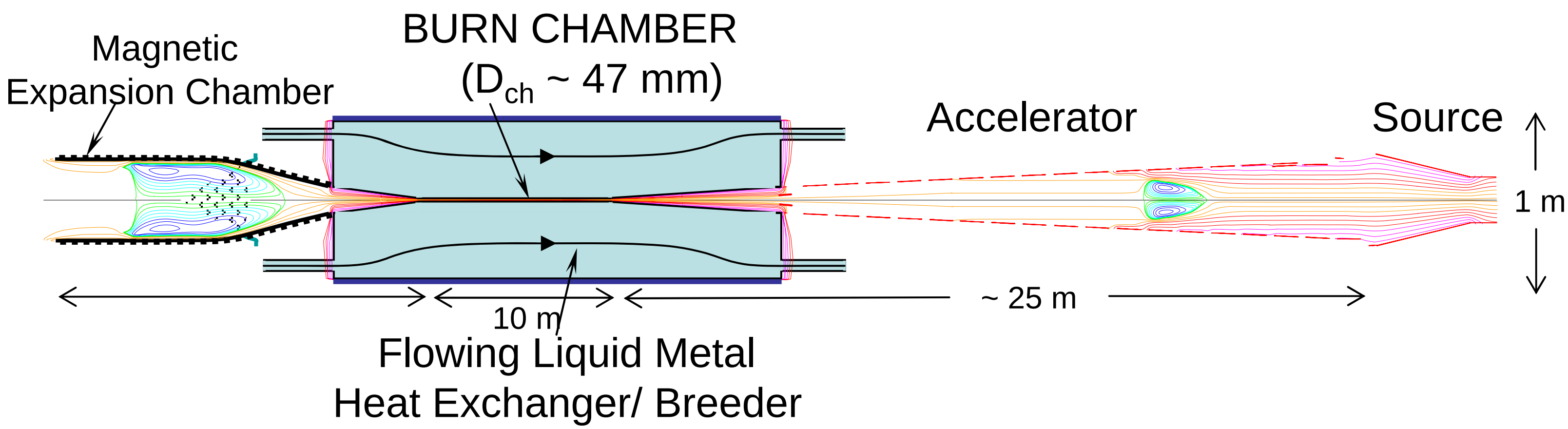
t = 15 μs   t = 16 μs   t = 17 μs   t = 18 μs   t = 19 μs



- **This combination of timings captured and re-centered the FRC, compressing it to multi-keV temperature.**
- **The grid motion is stopped at 17.0 μs**
  - **The lower portion of the grid is shown in the inset.**

UNIVERSITY OF WASHINGTON

Outline of PHD Fusion Concept



1 - FRC formed at low energy (~30 kJ) and relatively low density (~10^{15} cm^{-3})

2 - FRC accelerated by low energy propagating magnetic field (~ 0.5 T) to

3 - FRC is wall compressed and heated as it decelerates into burn chamber

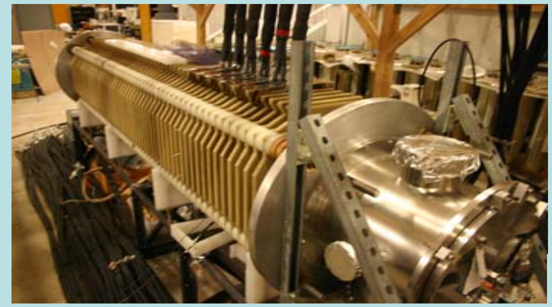
4 - FRC travels several meters during burn time minimizing wall loading

6 - FRC expands and cools converting thermal and magnetic energy back into stored electrical energy

Pulsed High Density (PHD) Fusion Experiment

Advantages

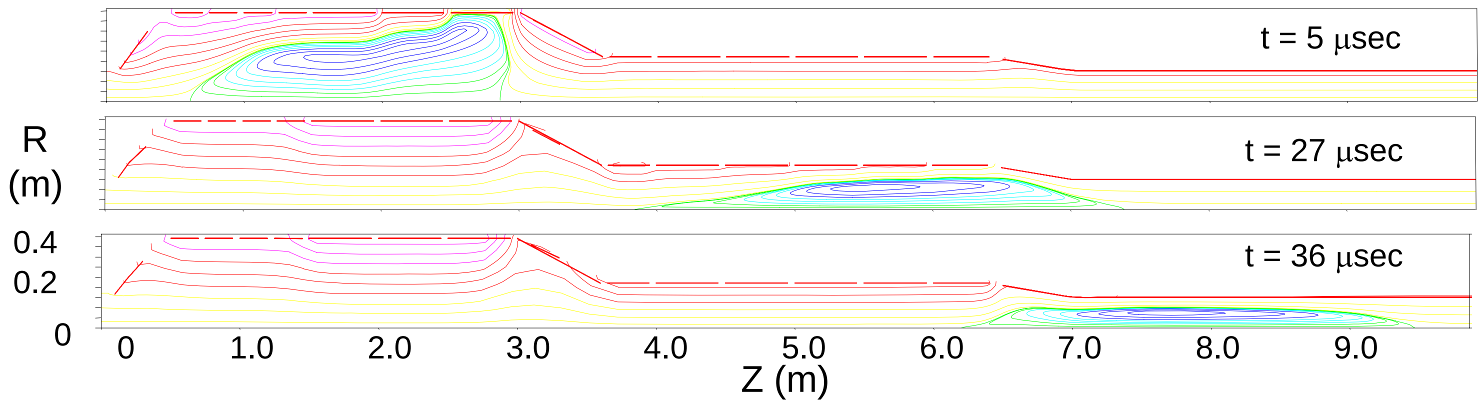
- Minimum B field at highest plasma pressure (β~1)
- Simple linear system – reactor wall is a steel pipe
- Variable output power ~ 10-100 MW not multi-GW
- Burn chamber well separated from plasmoid formation/heating.
- Direct electric power conversion with expansion of fusion heated plasmoid (Brayton cycle - η > 90%)
- Low mass system directly applicable to space propulsion
- Key physics and scaling have been demonstrated

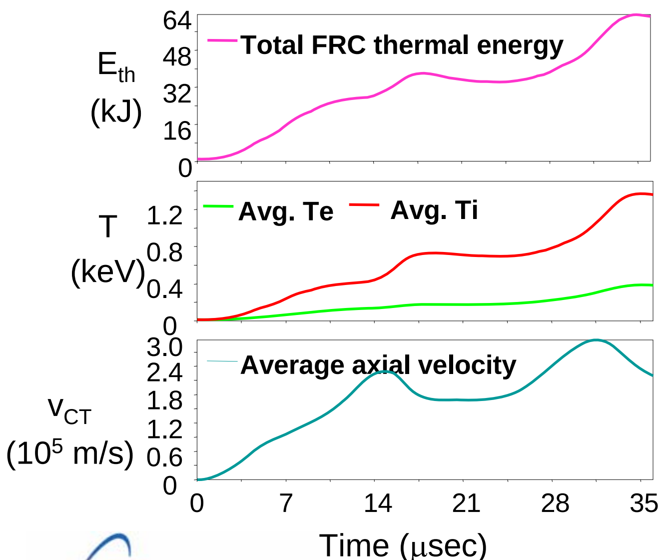


Current experiment to create initial FRC plasmoid for compression experiment

Fast energy storage 300 kJ at +/- 25 kV in 12 pairs of individually charged and triggered modules.

PHD Modeling

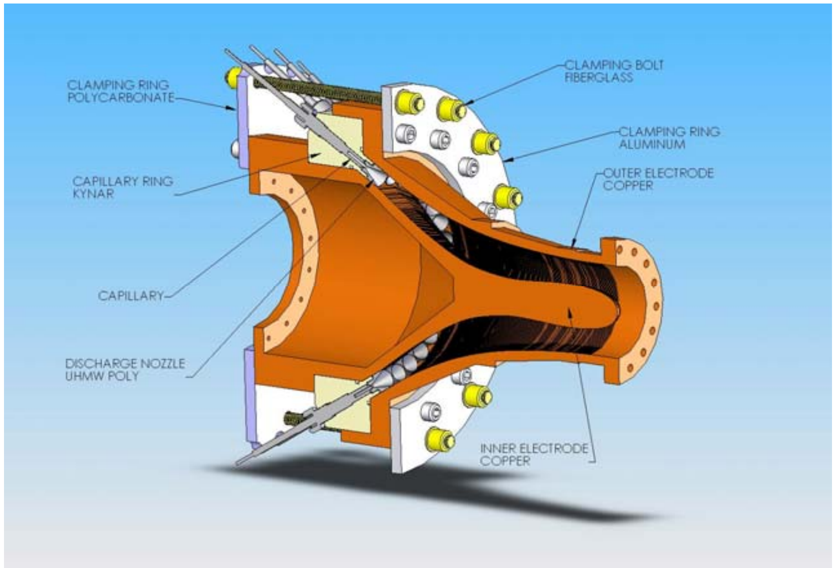


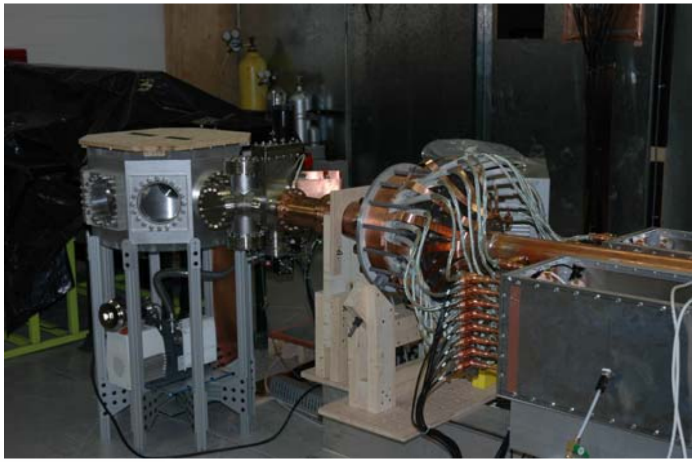


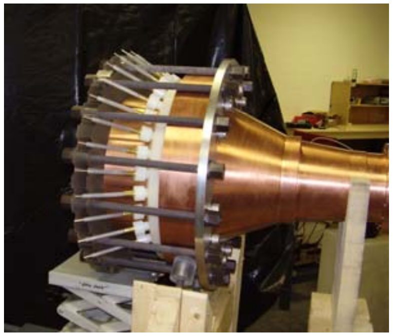
- Initial PHD studies are aimed at achieving keV plasmas with significantly increased confinement parameters
- PHD has been designed to determine and explore FRC stability boundary in both in situ and translating CTs
- PHD will provide the parameters for fusion gain in the reactor regime
- FRC acceleration has been demonstrated previously with ($a > 10^{10}$ m/s^2), and PHD will extend these results in compression

Technologies for advanced MTF: Plasma Jet Research at HyperV Technologies

- **Mission:** Experimental plasma research to develop high momentum-flux-density plasma jets. >100 ug, >200 km/s, 10^{16}-10^{17}cm^{-3}, >Mach 10
- **Applications:** Disruption mitigation, refueling, driving rotations, magneto-inertial fusion (plasma liner).
- **Approach:** Highly collisional armature, preformed plasma with high speed injection from electrothermal plasma discharge.







Full-scale accelerator module with 32 capillary injectors built and tested. Unit shown will be installed on MCX at University of Maryland

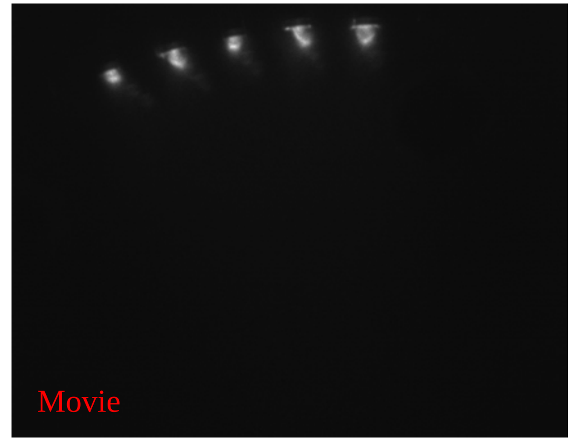
Plasma Jet Injectors

STATUS

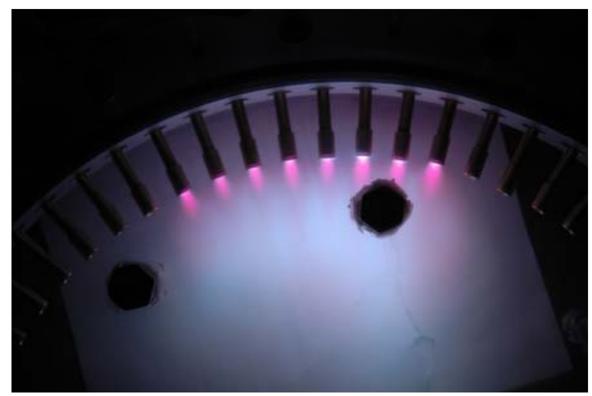
Developing highly collisional preformed plasma armature using high speed symmetric injection from multiple low jitter electrothermal discharges.

Experimental testing underway on full scale accelerator modules and several test fixtures for developing advanced injector components.

First module soon to be installed on MCX at Maryland.



5 capillary injectors firing simultaneously into 60 mTorr vacuum at 10.8 km/s. Obtained from PI-Max camera using 50 ns gate shutter with 500 ns between frames.



Multiple jets firing in visible light. 1 second exposure. Dark blotches in field of view are external bolts.

Technical Challenges

- Pure high density deuterium injectors
- Blow-by (a dynamical instability)
- MHD instabilities (filamentation, Rayleigh-Taylor)

Summary

- Magnetized Target Fusion explores a physics regime for fusion intermediate between MFE and IFE, with interesting scaling, and a uniquely different set of opportunities and problems compared to conventional approaches to fusion.
- Experiments and modeling of the elements necessary for demonstrating Magnetized Target Fusion in the laboratory are progressing, funded by Office of Fusion Energy Sciences.
- The first multi-keV deuterium FRC high energy density plasmas are expected in a liner/plasma implosion demonstration at the Air Force Research Lab Shiva Star facility, in FY2008