FIELD-REVERSED CONFIGURATION (FRC) ADIABATIC COMPRESSION-HEATING EXPERIMENT AT AFRL

Chris Grabowski, Don Gale, Jerry Parker, Dale Ralph, and Wayne Sommars
Science Applications International Corporation, 2109 Air Park Rd SE
Albuquerque, NM 87106 USA

James Degnan, Matt Domonkos, Ed Ruden, and Wes Tucker
Air Force Research Laboratory, Directed Energy Directorate, 3550 Aberdeen Avenue SE
Kirtland AFB, NM 87117-5776 USA

Tom Intrator, Richard Renneke, Peter Turchi, Bill Waganaar, and Glen Wurden
Los Alamos National Laboratory
Los Alamos, NM 87545 USA

This research was sponsored by DOE-OFES
ABSTRACT

An experiment to form, translate, and adiabatically compress a plasma in a Field-Reversed Configuration (FRC) is now being assembled at the Air Force Research Laboratory in Albuquerque, NM. Over the past five years, the AFRL has been working in close collaboration with Los Alamos National Laboratory’s FRC formation experiment, FRX-L. The AFRL experiment will reproduce the electrical properties of FRX-L to ensure that FRCs of similar parameters are formed. After formation, the FRC will be translated into the interior of a 10-cm diameter, 30-cm long aluminum solid liner with a nominal 1-mm wall thickness. The Shiva Star Capacitor Bank will then be used to implode this liner and compress the FRC to magnetized target fusion (MTF) relevant densities and temperatures.

Based upon FRX-L’s present configuration, FRC formation in the AFRL experiment will require four separate capacitor banks. These banks include two slow rise-time banks to first establish both a bias magnetic field in a 10-cm diameter, 36- to 45-cm long theta discharge region and a higher-intensity cusp field at each end of this region. Inside the theta discharge region will be a 50 to 100 mTorr deuterium pre-fill that a fast bank will pre-ionize with an oscillating magnetic field comparable to the bias field. The last bank will drive a reverse field in the theta discharge region with an amplitude approximately 10 times greater than the initial bias field. This last bank will be crowbarred to lengthen decay time and FRC lifetime. To translate the FRC from the theta discharge region into the liner, one or two additional slow banks are needed to set up a guide field to the liner and a mirror field at the opposite end of the liner.

The present status of the AFRL compression-heating experiment will be discussed, along with relevant circuit parameters and hardware designs for the capacitor banks. A proposed design for the integrated theta discharge, translation, and liner regions will also be presented.
EXPERIMENTAL GOALS FOR THE AFRL EXPERIMENT

• Duplicate (electrically) LANL’s FRX-L experiment
• Characterize the pulsed power system well enough so that FRCs can be formed reliably that have plasma parameters similar to the FRCs formed with FRX-L
• Demonstrate the ability to translate an FRC sufficiently far and through a liner electrode aperture
• Perform several liner implosion experiments with an integrated formation and compression setup on Shiva Star to demonstrate fusion
PLASMA PARAMETERS

• Present and Projected FRC Parameters\(^1\)
  
  – *In formation region of experiment*
    • \(n \sim 10^{17} \text{ cm}^{-3}\)
    • \(T \sim 100 – 300 \text{ eV}\)
    • Poloidal B \(\sim 5 \text{ T}\)
  
  – *After solid liner compression*
    • \(n > 10^{19} \text{ cm}^{-3}\)
    • \(T \rightarrow \text{several keV}\)
    • Poloidal B \(\sim 500 \text{ T}\)

• Energy confinement time \(> 10 \mu \text{s needed}\)
BACKGROUND

• Advantages of FRC’s for a fusion energy concept$^2$:
  – Simple cylindrical geometry
  – High $\beta$ ($\beta \sim 1$) and high power density $\rightarrow$ compact system
  – Translatable $\rightarrow$ formation and adiabatic heating regions can be separated
  – Natural separatrix diverter – isolation from walls, impurity barrier

Figure from Ref. [1].
BACKGROUND (Cont.)

- **How the FRC is formed**:  

1) *Pre-Ionization*: fill with gas; apply bias, cusp fields; then ionize the gas.

2) *Field Reversal*: apply reverse field ⇒ plasma implodes.

3) *Reconnection*: magnetic field lines tear and reconnect forming closed loops.

4) *Contraction To Equilibrium*: FRC contracts radially and axially until reaching an equilibrium state.
PULSED POWER REQUIREMENTS

• Four banks required for FRC formation
  – *Slow bank for Bias field* (0.3 ~ 0.5 T)
  – *Slow bank for Cusp fields at ends of formation region* (>0.5 T)
  – *Fast bank to pre-ionize (PI) the gas* (0.3 ~ 0.5 T, ~250 kHz)
  – *Moderately fast, high-energy Main bank for field reversal* (3.0 ~ 5.0 T, 2.5 ~ 3.0 µs risetime)

• One or two additional banks need for FRC translation to liner region
  – *Slow bank for Guide fields* (3.0 ~ 5.0 T)
  – *Possibly a second bank to generate Mirror at end of liner* (>5.0 T), could also perhaps be generated with Guide bank
PLANNED LAYOUT FOR BANKS

- Bias, PI, and Main banks all drive same set of coils → care must be taken to isolate the banks from each other.
- All banks must float; a single ground point is established at the vacuum vessel.
BIAS BANK DESIGN

- One, possibly two, cap bank modules (already existing), max C ~2.55 mF per module
- Switched with ignitrons
- 2.2 µH “Bias inductor” to isolate from PI and Main banks

Proposed Bias bank configuration.
PI BANK DESIGN

• Single Maxwell 2.1 μF capacitor
• Switched with single rail-gap switch
• Want bank current to ring at 250 kHz, as is the case for FRX-L ⇒ total circuit L should be ~193.0 nH

Photo of the Pre-Ionization bank during assembly.
MAIN BANK DESIGN

- Single Shiva Star bank module but with caps turned sideways to reduce bank height
- \( C_{\text{upper}} = C_{\text{lower}} = 72 \ \mu\text{F} \)
- Switched with quad set of rail-gap switches
- Want \( t_{1/4} = 2.6 \sim 3 \ \mu\text{s} \Rightarrow \) total circuit \( L \) should be \( 76.1 \sim 101.3 \ \text{nH} \)

Photo of the nearly-completed Main bank.
MAIN BANK CROWBAR SWITCH

- Main bank current is crowbarred near its maximum to extend FRC lifetime
- Comprised of quad set of rail-gap switches
- Theta coil and Main bank current loops through crowbar switch have no shared volume

Photo of crowbar switch during assembly.

Solid Works® illustration of side view of crowbar switch.
Calculated Theta Coil Current:
(Typical FRX-L parameters)
Main bank +/- 35 kV, trig @ 116.45 µs
Bias bank – 7 kV, trig @ 0
PI bank + 53 kV, trig @ 110.8 µs
Crowbar, trig @ 119.2 µs

• Number of PI bank oscillations can be varied, affects initial plasma parameters
• Current in Main Bank loop of crowbar switch does induce a small voltage across the crowbar switch (V = L dI/dt)
• Effect on crowbarred theta coil current is relatively small as switch inductance is less than transmission line and theta coil inductance
• The Theta coil will be a segmented (4–5 segments), single turn Al coil; each segment ~8.25 cm wide with 1-cm gap between

• A compact cable header is needed for the coil to feed current from the Bias, PI, and Main banks ⇒ a “matrix-style” header has been chosen

Blue = Bias
Red = PI
Green = Main
CUSP BANK DESIGN

- One or two cap bank modules, similar to that used for the Bias bank
- $C_{\text{cusp}}$ still to be determined; each module up to 2.55 mF
- Switched with ignitrons
- Each Cusp coil 16 turns of hollow copper conductor (square cross section); coil i.d. 14 cm, coil thickness 2.5 cm

AFRL cap bank modules in storage. Each module has up to fifteen 170-µF caps.
FORMATION, TRANSLATION, AND IMPLOSION REGIONS

- After the FRC is formed, it will need to be translated a short distance into the liner.
- Additional field coils will be required to guide the FRC to the liner.
- A mirror field will also be needed to slow the FRC once it enters the liner.

Formation, translation, and implosion of an FRC$^3$. 
• Under Shiva Star, the FRC will need to be translated vertically
• Theta coils segments with varying radii, arranged to form a cone, may be used to initiate translation near the end of formation
• Field coils around liner will likely have to be replaced each shot
GUIDE AND MIRROR COIL BANKS

- Two cap bank modules (one per bank) similar to that used for the Bias bank
- $C_{\text{Guide}}$ and $C_{\text{Mirror}}$ still to be determined; each module up to 2.55 mF
- Switched with ignitrons
- Guide and Mirror coil dimensions, current requirements still to be determined

AFRL cap bank modules in storage. Each module has up to fifteen 170-µF caps.
• The Shiva Star Bank at AFRL will drive the liner implosion$^{4, 5}$

- $C_{\text{Shiva}} = 1.296 \text{ mF}$, $V_{\text{charge}} = 84 \pm 1 \text{ kV}$

- Al. liner will have 10 cm diam., 30 cm length, nominal 1 mm wall thickness

- 8-cm diam. apertures in electrodes allow FRC to translate into liner shortly after implosion begins$^6$

The Shiva Star bank during a liner implosion shot.
DATA FROM RECENT DEFORMABLE CONTACT LINER SHOT

- Radiographs below show highly uniform radial implosion along length of axis$^6$

$t = 0 \mu s$

FRC will be translated into liner shortly after current flow begins

$t = 20.96 \mu s$

$t = 21.88 \mu s$
• Slow banks, power supplies, trigger units will be placed between B- and C-Arm

• Fast banks and vacuum vessel will be tested to the side, moved under Shiva only when preparing for FRC formation/compression test

⇒ Fast bank cable transmission lines must be kept short to reduce inductance

⇒ FRC vacuum vessel cannot be kept under Shiva due to other on-going tests
STATUS AND SUMMARY

• The broad knowledge base from the FRX-L FRC formation experiments\textsuperscript{1,3,7} and the AFRL liner implosion experiments on Shiva Star\textsuperscript{4,5,6} are helping to guide the design and assembly of this experiment

• Many of the pulsed power bank designs are completed

• Much of the hardware is in house and being assembled at this time

• LANL/FRX-L personnel are currently working on translation hardware design

• FRC characterization tests should begin later this year; data from these tests will be compared with that from FRX-L
REFERENCES


