Techniques to extend FRC lifetimes for magnetized target fusion implosions in FRCHX

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Outline of Presentation

• Intro to FRCHX at the Air Force Research Laboratory, Albuquerque
• The problem of short FRC trapped-flux lifetime
  – Poor formation, inadequate flux trapping
  – Magnetic well not sufficiently deep, or not configured correctly
  – Late-time instabilities
• Efforts to extend the trapped-flux lifetime
  – Improved plasma pre-ionization via RF and other pulsed axial electric field breakdown assistance
  – Optimized bank timing and trapping fields
  – Implementation of axial bias rings above the liner, used in conjunction with gas puff prefill, to control end shorting of the open magnetic field lines surrounding the FRC and thereby control its rotation
  – Stabilization with plasma guns
• Recent computational modeling results
  – Better comparison with experiment
  – Examination of earlier initiation of the liner implosion
  – Improved compression with better-formed (more trapped flux) FRC

Summary
FRCHX is at the SHIVA STAR Air Force facility in Albuquerque

Shiva Star can store 9 MJ of energy with 1.3 mF of capacitors, at up to 120kV. More typically, at 4.5 MJ, it delivers 12 MA of current to crush a 30-cm tall, 10 cm diameter, 1 mm thick, 300 gm Aluminum cylindrical liner load in FRCHX. The FRC plasma injector can be operated under the center of SHIVA for implosions, or off to the side for setup testing in the high bay. It takes a dedicated crew 2-3 weeks to move the experiment from one position to the other.
The Field Reversed Compression and Heating Experiment (FRCHX) at the Air Force Research Lab

FRCHX is designed to be imploded for integrated physics tests of MTF

- The plasma injector forms an FRC using conical theta coils, and translates the plasma into a 30 cm long aluminum liner.
- The liner is imploded by 12 MA of current from the SHIVA bank, over a timescale of 23 microseconds (start to finish).
- These are destructive, high energy shots (4.5 MJ, from which ~1/3 is coupled to the liner).
- A team of ~ 20 people work to model, design, diagnose, prepare, and rebuild each implosion test. However, many non-implosion setup shots are taken to optimize the FRC plasma injection and capture, prior to an implosion.
Our first integrated implosion test was 34 months ago

- The electrical subsystems performed as requested. Bank timing and currents were good. But plasma compression signatures were absent (no soft x-ray increase, no spectroscopy change, no neutrons measured) at the expected time of peak compression.

- **What is taking us so long to take the second implosion shot?**
  - We were prepared to take a second, identical shot, within one month (should the first one have failed). But from an engineering point of view, it worked….so we pondered what to do.
  - After reconfiguring the experiment off to the side of SHIVA, we verified the plasma arrival timing, by building a set of internal magnetic probes for the liner region, and doing an extensive set of FRC shots. This took about 6 months. We also added an end-on high speed framing camera.
  - Basic problem: The lifetime was too short. No FRC plasma was present by the later half of the implosion. The plasma was decaying too quickly. Too little flux? Instabilities? Not being fully captured?
  - During the last 20 months, we have been trying methods to extend the lifetime of our captured FRC plasma in the aluminum liner.
Formation and Translation of the FRC with FRCHX

- The FRC is formed in a segmented Theta coil and then ejected from the formation region by $J_\theta \times B_r$ forces.
- Fields along the short translation region keep the FRC from expanding.
- Lower and Upper mirror fields form a capture region for the FRC that stops it within the center of the liner.

Formation in Conical Theta Coil

Capture

Translation

~1 m
The FRCHX Formation, Translation, Capture Pulsed Power Systems

- **Bias bank** – Two capacitor bank modules, ~2.5 mF per module
- **PI (Pre-Ionization) bank** – Single 2.1 µF capacitor, oscillation frequency of ~230 kHz
- **Main bank** – Single Shiva Star bank module, caps turned sideways to reduce bank height ($C_{\text{upper}} = C_{\text{lower}} = 72$ µF); bank is crowbarred near peak current
- **Upper and Lower Cusp banks** – Three 500 µF capacitors each, switched with ignitrons
- **Guide/Mirror Bank** – Total capacitance of 12 mF, switched with 6 ignitrons
- **Shiva Star** – To drive the liner implosion, 36 modules, ~1.3 mF total capacitance

We are splitting this bank, to allow flexibility to enable delayed FRC injection.
Simulation, Experiment of Solid Liner Implosion on Vacuum B-Field

- MACH2 results for Shiva Star solid liner compression, ~2 Tesla initial axial B-field
- MHD simulation using experimental current agrees well with radiography with regard to liner radius versus time
- Calculated peak field is 540 Tesla; time between peak compression and start of current is ~25 µs
FRC Plasma Parameters (design point)

- Pre- and Post-Compression FRC Parameters
  - In formation region of experiment
    - \( n \sim 10^{17} \text{ cm}^{-3} \)
    - \( T \sim 100 - 300 \text{ eV} \)
    - Poloidal B \( \sim 2 - 5 \text{ T} \)
  - After solid liner compression
    - \( n > 10^{19} \text{ cm}^{-3} \)
    - \( T \rightarrow \text{several keV} \)
    - Poloidal B \( \sim 200 - 500 \text{ T} \)

- Initial plasma lifetime \( \geq 20 \mu\text{s} \) needed

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Guide/Mirror fields are set up first in the Translation and Capture regions.

The Bias field in the Formation region follows approximately 6 ms later.

Upper, Lower Cusp fields are set up 80 ~ 85 μs after Bias.

PI and Main banks are triggered last to form and push the FRC toward the liner and Capture region.

Shiva Star discharge can be a few μs before Main discharge (and possibly earlier) to reduce the time the FRC must remain in the Capture region before compression.

### Probe Location Distance Below Liner Top (cm)

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<th>Probe Location</th>
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<td>F</td>
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<tr>
<td>D</td>
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FRC Trapped-Flux Lifetime was shorter than desired

- Several factors could result in shortened lifetimes:
  - Poor formation, inadequate flux trapping (Formation Region)
  - Magnetic well not sufficiently deep, or not configured correctly (Capture Region)
  - Late-time instabilities (Translation and Capture Regions)
Lifetime in the capture region is reproducible, as measured by internal magnetic probes along the wall of the liner.

Magnetic probe measurements in middle of the capture region:

- FRC formation occurs at 36.089 ~ 36.090 ms on this time base.
  - Total trapped-flux lifetime (to half max of $R_{ex\_fl}$ signal) is 15 ~ 18 µs.
  - But lifetime in the liner is only 7-8 usec.
Multi-Chord Interferometry Shows Varied Phenomena at End of FRC Life

- A “normal” FRC decay is seen in the capture region here
  - Density (line integrated) rises on all three chords and then falls off on all three chords.
  - Greater flux trapping would perhaps lengthen the decay, extend lifetime
Multi-Chord Interferometry Shows Varied Phenomena at End of FRC Life

- Anomalous events observed at 36.099 and 36.101 ms
  - The diameter chord (red) drops abruptly, the FRC then appears to move off-axis
  - Perhaps from tilt or rotational instabilities, or a combination of the two
Hadland Fast-Framing Camera Shows Evidence of Late-Time Instability

- The Hadland images show a sequence of
  - straight translation (frames 1-5),
  - followed by transverse motion to the left (frames 6 – 10),
  - until the FRC then appears to impact the wall (frames 11 – 12).
- Each frame 100 ns exposure, 1μs between frames
Evidence of Plasma Rotation in the Hadland Images

Plasma rotation inferred from images by noting changes in angular position of plasma features from frame to frame. Note slowing of rotation in later frames. (Motion is more evident when the frames are viewed as a movie.)

Image 1 @ 9.59697 ms (12.97 μs after PI start); 1 μs between frames, 100 ns exposure.
Gated axial view Optical Spectroscopy shows late-time Impurities

- Optical spectra obtained with axial view, 3-μs exposures, indicate low impurities until FRC reaches 9 cm aperture in the lower liner electrode.
- We will repeat this without interior magnetic probes and with radial spatial resolution & tighter collimation to see if inner portion is cleaner. (Three gated spectrometers are now installed).
FRC Trapped-Flux Lifetime was shorter than desired

Approaches to address the short lifetime:

- Investigated last year
  - RF “pre-pre-ionization”
  - Active rotation control with gas puffing
  - Varying (“tuning”) bank parameters

- Being implemented now:
  - Plasma injection via plasma gun(s) to
    → improve flux trapping during formation
    → provide stabilization during translation and capture
  - Redesign Mirror field profile (longer & deeper)
  - Mitigation…..fire the FRC late (10-12 usec after the start of implosion…but have to compensate for dynamic nature of entry mirror field by that time)
Motivation for RF Pre-Preionization

- The intention during the FRC formation process is to generate the initial plasma with the Bias field embedded.
- Historically (and in present experiments), however, the ringing-theta-pinch-induced (PI) breakdown occurs only when the net field (Bias+PI) is close to zero.
- This appears to be due to magnetic insulation effects.
- The graphs below illustrate: first light at the “D”, “F”, and “H” positions in the formation region appears just before the net axial magnetic field goes to zero.
Application of Axial RF E-Fields to Enable Breakdown When B is Larger

- A ringing theta pinch induces breakdown via an azimuthal electric field
- Application of an axial electric field would not have to overcome the insulating effects of the Bias field, as the two fields would be parallel
- Use of RF electric fields appears to have helped improve FRC parameters in past experiments
- We are investigating the benefits to plasma formation of modest axial RF electric fields applied over a long duration (100’s of volts over milliseconds), as well as large amplitude electric fields applied for a very short-duration (a few 10’s of kV for 10’s of nanoseconds)

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5 G. Kiuttu, et. al., “RF Pre-Preionization for the FRCHX Experiment,” poster presentation, this conference.
Electrodes (outside the quartz tube) to Apply RF Electric Fields

- Two Cu foil strips, 1.9-cm wide, are wrapped inside grooves in two nylon rings (left)
- At the 1.9-cm-wide gaps between the ends of the foils, a layer of Kapton tape (2.5 ~ 3.5 mils thick) is placed over one end of the foil and under the other end to prevent breakdown between the two ends (left)
- The foil strips are potted in the Nylon rings with a silicon encapsulant (middle), and the rings are then placed near the ends of the Theta coil at Segments “B” and “I” as the Theta coil is being assembled (right)
- Low-amplitude, long-duration (250 ~ 500 V, 9.58 ms, 46.79 MHz) or large-amplitude, short-duration (~30 kV, 62 ~ 125 ns, 32 MHz) axial electric fields (∥ to B) are applied between the two rings
Long-Pulse, Lower-Power RF Pre-Preionization System Design

- Initial RF source power was only 1.0~1.5 kW…good enough for a glow.
New transient 20 kV, 30 MHz RF System

- To produce a higher power (Megawatt) RF discharge, a switched charged resonant cable system was built and tested.
- The system uses a YK-198 high-voltage cable that is DC charged up to 20 kV.
- It is charged and shorted using the components in a modified Titan Pulse Sciences model 40168 Trigger Amplifier.
- The 30-MHz damped (50-100 ns L/R decay time) ringing waveform is coupled capacitively to the RF electrodes around the plasma chamber.
Line-integrated electron density measurements, a) in the middle of the formation region and b) in the middle of the capture region, highlight the differences with and without RF.

**Notes:**
- Time = 0 in these graphs is the start of the Bias bank discharge.
- The short-pulse RF trigger is ~70 ns before the PI discharge; the long-pulse (CW) RF starts 9.58 ms before the PI and continues until the Main discharge.
- A 50-mTorr D2 pre-fill is used in the first three tests; an equivalent gas-puff is used for the last.
Breakdown at Higher B-Field (Cont.)

◊ Notes (cont):
  – The PI charge is 14% higher for the no-RF case
  – The Guide/Mirror voltage is 38% higher for the short-pulse RF test.

• A significant enhancement in the density (by a factor of 4 in the formation region) is observed with the use of the short-pulse RF source.

• While the density is nearly same between the CW RF and no-RF tests, it is noteworthy that the PI voltage was reduced in the long-pulse (CW) RF tests, and so more of the Bias field was present in the formation region when the gas was broken down.
FRC Excluded Flux Radii from Tests With and Without RF

Data are from the same tests as on Slide 24. a) $R_{ex_{-}fi}$ at the formation region top, b) $R_{ex_{-}fl}$ at the capture region midplane.

- Tests with the long pulse (CW) RF source show in the capture region an incrementally larger radius with a slightly wider full width, half maximum (FWHM) compared with the test that did not have RF.
Capture Region Optimization: A Deeper and/or Wider Magnetic Well

- COMSOL calculations were performed to examine how the magnetic well can be made deeper or otherwise modified to better trap the FRC
  - The original (baseline) field profile (no modifications) is shown on top right
  - The lower right graph shows the results when adding a flux limiting/excluding plate between the second and third Upper Mirror coils
- Since Upper Mirror field strength is reduced, additional coils or windings will be required
- A stronger Upper Mirror is desired, regardless, to reduce stretching of the FRC above the capture region and possible mass loss
- A wider magnetic well may also improve capture and reduce this stretching
- Through further iteration of the design in COMSOL, the field profile can be tailored to match profiles predicted by MACH2 and other codes as being optimum.
Mirror Design Consideration – Azimuthal Induced Current in the Slotted Return Conductor

8 slot design varies from ideal near entrance mirror.
Biased Equipotential Rings for Rotation Control

- Steinhauer’s steady state analysis of FRC rotation due to the boundary potential of a perfectly conducting extended MHD plasma (obeying generalized Ohm’s law) is used to estimate the optimal voltage as being of order of the electron temperature in eV (hundred of volts).

- Steinhauer’s analysis was generalized for the purpose of active field control of an FRC in Ref. [8].

- Based upon this analysis, a set of control rings has been built to implement this scheme to control rotation along most of the open flux. Gas puffing is essential for managing the amount of gas around the rings so that the bias may be maintained for a sufficient amount of time.

“Connecting” the Biased Ring Assembly to the FRC

- A low-density conducting path (i.e., a plasma) is needed between the control rings and the FRC so that the rings can “transmit” the electric field to the region just outside the separatrix around the FRC.
- Initially this plasma has been that which was propagating in front of the FRC, but this plasma arrives too late to allow the rings to begin influencing the FRC rotation.
- A low-pressure pre-fill in the FRCHX vacuum vessel and an external means of breaking down this pre-fill in the ring region is currently being characterized in experiments, as was mentioned.
- Eventually a separate gas puff valve will be placed on top of the experiment to directly inject gas into the Ring region.
- Another triggering mechanism being considered for the control rings is a plasma gun, which can connect the rings to the FRC more quickly.
- Indeed, the plasma gun itself may prove to be an effective means of stabilization and counter rotation control for the FRC.
Use of Plasma Guns for FRC Stabilization, and Improvement of Formation

- T. Asai’s group in Japan has recently reported on experiments to inject toroidal flux via use of a plasma gun for the purpose of introducing a counter-torsional shear flow adjacent to an FRC and thereby control rotation.\textsuperscript{9}
- M. Tuszewski and L. Steinhauer have also noted the rotational and other stabilizing benefits associated with the use of plasma guns in Tri Alpha Energy’s C-2 Device.\textsuperscript{10,11}
- The plasmoid from the plasma gun, once it envelopes the FRC, appears to directly apply the needed counter-rotational E×B forces to the FRC at its separatrix.
- As an alternative to the RF pre-ionization, injection of externally formed plasma from one or more coaxial plasma guns into the FRC formation region is also being pursued.
- The guns would provide a means of injecting an already-formed plasma directly onto the Bias field lines, thereby enabling a more substantial field to be present within the plasma when FRC formation takes place.

\textsuperscript{11} L.C. Steinhauer, private communication, Sept. 2012.
A Russian Plasma Gun for FRCHX

- We have recently obtained a plasma gun, complete with power supplies, from EMC2 in San Diego.
  - Arc current up to 800 amps, 100 v
  - Magnetization coil (25 amps)
  - Ignition spark (6kV, 200 usec)
  - Anode and Cathode gas puff valves
  - Plasma flow 10-20 equivalent amps
  - Ion temperature 2-4 eV, pulse duration up to 5 ms, typical gas efficiency 50-90%
- We mounted it on a pressure test stand (photo, left), and then will move it to the bottom of FRCHX
Status of 2D Simulations

- These are all simulations of experiments with both fixed and imploding aluminum liners.

- The simulations are performed using MACH2.
  - They include SESAME table EOS's and resistivities for materials
  - All three components of the magnetic fields,
  - An energy-conserving model of the imploding deformable liner
  - Flux-based field modeling of the time-dependent poloidal fields.
  - Adaptive gridding for the FRC, Lagrangian for the liner.

- We have attempted to capture as much of the physical geometry as we can.

- AFRL’s well-diagnosed static liner experiments are providing a lot of data we can use within our simulations and as a basis for validation of the simulation’s representation of the experiment.
We have greatly improved our ability to model the FRCs that are being formed by using the ‘time of first light’ in the experimental data as an indicator of when the ionization and flux-trapping occurs, for our modeling of the preionization.

This technique produces capture region integrated B-dot signatures that are very much like those measured in the corresponding experiments.

This particular comparison is based on an experiment performed in March of last year, using low level RF-induced pre-ionization.

Only part of the FRC was captured in the mirror fields in the static liner; some mass and flux escaped out the top (left hand side in picture).

These times are relative to the firing of the FRC’s main theta coil.
Simulations of FRCs in Imploding Liners

- The imploding liner experiments have an added complication of the timing of the FRC formation main bank relative to the main bank of the liner implosion.
  - In order to maximize the lifetime of the FRC within the imploding liner, it is useful to have the liner accelerated and imploding when the FRC arrives, and the compression of the mirror fields by the liner must be accounted for.
- Here we have selected a 5.65 us delay to put the low-RF FRC at the imploding liner ~12 us into the implosion.
  - The liner’s radius is ~80% of its original 4.89 cm, and the mirror fields have increased by 64%.
  - Only a fraction of this FRC was captured.
- The simulations follow the compression of FRC by the liner – shown below with the liner radius at 5.06 mm. Notice that our 1 cm long FRC (16 ms) is now ~8 mm long.

These times are relative to the firing of the Main bank.
Capturing More Flux in the FRC

• The simulations have also taught us that the amount of flux trapped during pre-ionization, and hence in the initial FRC, affects the lifetime and the robustness of the FRC.

• We performed a similar compression simulation with data from another March 2012 test with higher RF and higher current at the time of first light.
  – This FRC has 67% more flux after its formation than the FRC we have been discussing. (1.257 mWb vs 0.754 mWb).

• We captured more of the FRC, and it
  • Has more flux (0.415 mWb vs. 0.346 mWb);
  • Is hotter (273 eV vs. 209 eV);
  • Is less dense ($n_i = 2.6 \times 10^{16} \text{ cm}^{-3}$ vs. $3.3 \times 10^{16} \text{ cm}^{-3}$);
  • Is captured sooner, but a slightly earlier capture time means less compression has occurred;
  • Has a factor of 25 higher yield at 5 mm liner radius ($2 \times 10^9$ vs. $8 \times 10^7$).
Summary

- **Total trapped-flux lifetimes** of FRCs formed with FRCHX have reached 15~18 \( \mu \)s; with lifetimes of up to 12 \( \mu \)s in the capture region. We still aren’t capturing it all.
- Tests have been performed using an RF **pre-preionization**, and a more-energetic, higher-frequency PI bank is being explored. Injection of externally formed plasma from one or more coaxial plasma guns is also being pursued.
- Efforts to actively **support the electric fields** at the ends of the open magnetic field lines are underway, as the shorting of these fields leads to rotation and subsequent break-up of the FRC.
- Axial view fast photography provides **evidence of rotation** of translating and trapped FRCs, as well as evidence of slowing of that rotation when biased rings used – however this slowing occurs when or after FRC has deteriorated.
- A **redesign of the magnetic field profile** around the capture region is being done to better confine and capture the FRC and reduce mass and flux loss through the magnetic mirrors at each end.
- 2D-MHD simulations indicate the feasibility of **increased delay** between the start of the liner compression to the completion of FRC formation in order to reduce the required FRC lifetime for compression. A delay of 10-12 \( \mu \)s will be used on the next shot.
- **Hardware** will be moved under Shiva in April 2013, for the next implosion shot.
(Backup Slides)
Rotation Control for \( n=2 \) Stabilization

• An FRC, once formed, starts to rotate due, in part, to plasma conditions (lower temperature, higher density) at the vacuum chamber wall where the open magnetic field lines outside the separatrix exit the system.

• Generalized Ohm’s Law’s \( \nabla p_e \) term in the electric field implies that a non-rotating FRC will have an E field crossing the B field lines at the wall.\(^6\)

• Whether the wall is dielectric or (especially) metal, the conductivity of the wall or plasma layer there will carry current and eventually short out this E field. This current and its associated B field introduce torque at the separatrix and cause unstable viscous sheared flow across the separatrix, which leads to rotation of the FRC.\(^7\)

→ Supporting this E field with an external circuit coupled to conducting rings placed in the B-field exit region should prevent rotation.


The Biased Ring Assembly and Biasing Capacitor Bank

- Rings were initially unbiased; voltages that developed upon the rings were monitored during tests.
- The first biasing scheme (right) applied a graded voltage to the rings.
- With this setup, it was seen that 1 or more rings could be biased at the same voltage, while others were left unbiased. This led to the next biasing scheme (lower right).
- Inductances in the bank and ring connections were reduced at this time to enable faster response.
FRC Excluded Flux Radii Measured in Tests Utilizing the Biased Rings

- The graph to the left shows FRC excluded flux radii measured in the center of the capture region during tests with increasing Control Ring bias voltages.

- The Biased Ring circuit was configured to provide a uniform Bias to Rings 1, 2, and 3; Ring 4 was floating and connected to a voltage monitor.

→ An incremental increase in the FWHM of the excluded flux radius was observed as the bias voltage was increased from 0 V to 600 ~ 800 V

→ Above 800 V the radius and its FWHM in the capture region began to decrease

→ This result may be caused by the applied counter-rotational electric field being too large and thus leading to greater instability
Uniform Bias Applied to the Lowest Three Rings in the Assembly

- That more significant improvements in excluded flux radius FWHM were not observed may be from too long of a delay in “connecting” the Control Rings to the FRC.
- To the right, an overlay is shown of the current waveforms measured for each of the rings during a test with an 800 V bias applied to Rings 1, 2, and 3.
- Also shown are the voltage measured on the fourth Ring and the integrated T4 (middle of capture region) and T6 (just below Ring 1) B-dot probe signals.

→ The Ring 4 voltage begins rising (to ~550 V) and a low-level discharge current (~100’s A) through Rings 1, 2, and 3 starts when the Main bank discharge begins (at ~133.3 μs).
→ It is not until the plasma front reaches the Ring region, indicated by the rise in the T6 B-dot signal, that the Biased Ring circuit truly begins to discharge and produce the toroidal magnetic field and plasma needed to “tie” the electric field to the FRC plasma.
→ The FRC is arriving in the capture region during the Ring current rise; it may not experience the proper (constant) E-field needed for countering its rotation, and so it still dissipates after a fairly short lifetime.
Recently the four-ring assembly was replaced with a single-ring assembly.

The single ring is located between the former positions of Rings 2 and 3, and seven cables connect it to the capacitor bank to lower the circuit inductance still further.

A Trigger Ring, located between the Main Ring and the top plate, now allows the Ring circuit to be discharged upon command if there is sufficient gas in the Ring region.

A plasma gun is being fabricated to work in conjunction with the Ring circuit (e.g. to trigger it via gas puff or plasma emission) or to operate independently.