Technical Problem Analysis: MRT Instability in MTF Concepts

This analysis assesses the research conducted by Los Alamos National Laboratory (LANL) and the Air Force Research Laboratory (AFRL) to understand and mitigate the Magneto-Rayleigh-Taylor (MRT) instability within their joint Magnetized Target Fusion (MTF) program, culminating in the Field-Reversed Configuration Heating Experiment (FRCHX). The MRT instability, a magnetohydrodynamic instability that occurs when a magnetic field is used to accelerate a conducting fluid or plasma, represents a critical potential failure mode for any concept relying on the implosion of a solid metal liner to compress a plasma target.[1]

The central finding of this report is that circa 2013, the joint LANL/AFRL program was fundamentally constrained by a critical precursor challenge: achieving a sufficiently long-lived and stable Field-Reversed Configuration (FRC) plasma target. This prerequisite issue consumed the vast majority of the program's documented scientific and engineering efforts. As a result, dedicated research into the subsequent and equally critical problem of MRT instability mitigation during liner compression was not a programmatic priority and remained at a very low level of maturity.

1. Analysis of LANL Research: Capability vs. Application

Analysis of LANL's documented activities reveals a significant dichotomy between the laboratory's world-class institutional capabilities in instability modeling and diagnostics and the actual research focus of the specific groups executing the FRCHX experiment. While LANL possessed the necessary tools and expertise to address the MRT problem, these resources were not directed toward the MTF program, which was preoccupied with a more immediate technical obstacle.

Simulation & Modeling

A review of LANL's broader research portfolio establishes the laboratory as a global leader in the simulation of hydrodynamic and magnetohydrodynamic instabilities. Its theoretical divisions (T-Division) and applied physics groups have a long history of developing and utilizing advanced, multi-physics computational codes such as FLASH and HYDRA to model complex high-energy-density physics (HEDP) phenomena.[3] This expertise is routinely applied to understanding instability growth in major national security programs, including Inertial Confinement Fusion (ICF) at the National Ignition Facility (NIF) and Magnetized Liner Inertial Fusion (MagLIF) at Sandia National Laboratories.[1] These efforts demonstrate a deep institutional capability to simulate MRT evolution in both planar and cylindrical geometries under relevant conditions.

In stark contrast, the documented modeling efforts of the LANL P-24 Plasma Physics group, the lead entity for the FRCHX collaboration, were centered almost exclusively on the physics of the FRC plasma target. Their simulations, often employing codes like MACH2, focused on the initial stages of the MTF sequence: FRC formation via theta-pinch, translation out of the formation region, and capture within the liner prior to implosion.[9]

The key finding from this analysis is the conspicuous absence of published simulation work from either the P-24 group or LANL's theoretical divisions that specifically models MRT growth for the unique FRCHX configuration: a solid, relatively thick aluminum liner imploding onto a high-beta FRC plasma target. This absence is not an intelligence gap but rather a positive indicator of the program's scientific priorities. A logical research program would not dedicate significant computational resources to modeling a secondary failure mode (liner instability during compression) when the primary, antecedent failure mode (the plasma target dissipating *before* compression could be effective) had not yet been solved. The FRCHX program was demonstrably struggling to achieve the required FRC plasma lifetime of ~20 µs needed to match the liner implosion timescale.[9] The program's focus was therefore necessarily fixed on this more immediate and fundamental FRC lifetime problem, revealing a clear and logical prioritization of R&D challenges.

Diagnostic Development

LANL's institutional capability in diagnostic development mirrors its strength in simulation. The laboratory is a world leader in conceiving, building, and fielding advanced diagnostics for HEDLP experiments at premier facilities like Omega and NIF.[5] This includes a portfolio of sophisticated, high-resolution x-ray radiography techniques, such as the Crystal Backlighter Imager (CBI), which are specifically designed to image the fine-scale features of hydrodynamic and magnetohydrodynamic instabilities as they evolve.[1] This establishes that

LANL possessed the core competency to create and deploy the tools necessary to experimentally observe MRT growth on an imploding liner.

However, the actual diagnostic suite planned and employed for the FRCHX experiment was overwhelmingly focused on characterizing the FRC plasma target, not the liner's integrity. The documented diagnostic set included multi-chord laser interferometers to measure plasma density, various forms of spectroscopy to assess temperature and purity, and arrays of external magnetic probes to determine the plasma's shape, position, and trapped magnetic flux.[10] While diagnostics such as soft x-ray imaging and neutron detectors were planned for the final implosion shots, their primary purpose was to measure the state of the compressed plasma (i.e., temperature and fusion yield), not to provide high-resolution, time-resolved imaging of the liner's surface during its inward flight.[10]

No specialized diagnostic techniques were developed or fielded on FRCHX with the specific mission of detecting the onset or quantifying the growth of MRT instabilities on the solid aluminum liner. The choice of diagnostics for a complex experiment is a direct reflection of its scientific priorities. The FRCHX diagnostic suite was a perfect mirror of the FRC lifetime problem; the team needed to measure plasma density, temperature, and magnetic flux to understand why the FRC was decaying too quickly. High-resolution liner radiography was not pursued because the liner's stability was a secondary concern. If the plasma target was not viable, the liner's performance during compression was a moot point. This confirms, from an experimental hardware perspective, that MRT was not the primary research question being addressed by the program circa 2013.

2. Analysis of AFRL Collaboration: The "Hammer" and its Limitations

The Air Force Research Laboratory's role in the collaboration was to provide the "hammer"—the powerful liner implosion capability—to compress the FRC plasma target developed by LANL. This capability was the application of a mature, pre-existing defense technology. It was not a new research and development effort focused on creating novel MRT mitigation techniques specifically for the fusion energy mission.

Experimental Mitigation

The FRCHX experiment consistently utilized solid aluminum liners, typically of the 6061-T6 alloy, with dimensions of approximately 1 mm in thickness, 10 cm in diameter, and 30 cm in length.[9] The primary experimental objective documented in the final years of the program was the extension of the FRC plasma lifetime to match the ~20 µs timescale of the liner implosion.[9] The most current research from this period is captured in a July 2013 abstract by G.A. Wurden et al., which details a significant breakthrough. By physically lengthening the magnetic trap within the liner, the team successfully increased the FRC's trapped flux lifetime from a range of 8-11 µs to a much more promising 14-16 µs, bringing it close to the programmatic requirement.[9] This work on the plasma target itself represented the cutting edge of the program's publicly documented research.

There is no evidence in the available research of any systematic experimental campaigns conducted on FRCHX to test or develop MRT mitigation strategies. The research record shows a complete absence of studies on:

- **Alternative Liner Materials:** Unlike the parallel MagLIF program at Sandia, which investigated the use of beryllium liners, there is no indication that FRCHX explored materials other than aluminum.[9]
- **Magnetic Field Shaping:** There is no mention of experiments employing advanced stabilization techniques such as magnetic shear, dynamic screw pinches, or tailored current pulse shapes from the Shiva Star driver.[19]
- **Other Mitigation Techniques:** There is no evidence of the use of dielectric coatings or other methods that were being actively investigated in the broader HEDP community to suppress instability seeds.[25]

The experimental goal for the liner was to achieve a symmetric, uniform implosion using the existing, well-characterized hardware configuration developed for prior defense programs.[16] AFRL's contribution was its mature liner implosion capability, a technology honed over many years for other national security applications.[9] FRCHX was an

application of this capability to a new type of plasma target. It was not a program designed to *advance the state of the art* in liner stability physics. The broader research landscape clearly shows that MRT mitigation was an active, complex, and distinct field of study at the time.[21] The FRCHX program did not engage in this parallel research track because its mission was different: to determine if a pre-existing "hammer" (AFRL's liner implosion) could successfully compress a novel "nail" (LANL's FRC plasma). The failure to solve the "nail" problem—i.e., achieving a robust, long-lived FRC—meant the program never graduated to the subsequent stage of optimizing the "hammer."

Key Personnel

The AFRL contribution to the MTF collaboration was led by a core team of experts from the Directed Energy Directorate at Kirtland Air Force Base. Analysis of consistent co-authorship across numerous FRCHX-related publications and conference proceedings identifies the principal AFRL investigators.

Key AFRL Personnel	Primary Affiliation	Assessed Role & Expertise in MTF Collaboration	Key Supporting Evidence (Publication Topics)
Dr. John H. Degnan	AFRL Directed Energy Directorate, Pulsed Power Branch	**Lead, Liner Implosion Physics.** Senior expert on the design and execution of magnetically-driven solid liner implosions using the Shiva Star facility.	Solid/spherical liner implosions (pre-FRCHX); Integrated FRCHX compression results [18]
Dr. Edward L. Ruden	AFRL Directed Energy Directorate	**Principal Investigator, HEDP Diagnostics & Analysis.** Expertise in plasma diagnostics and continuum dynamics for integrated experiments.	Integrated FRCHX experiments; HEDP diagnostics; FRC lifetime studies [2]
Dr. Chris Grabowski	AFRL Directed Energy Directorate	**Principal Investigator, Pulsed Power & FRC Integration.** Expertise in pulsed power engineering (crowbar switches) and FRC	Integrated FRCHX experiments; Pulsed power hardware; FRC lifetime studies [14]

		formation/lifetime studies.	
Dr. Matthew T. Domonkos	AFRL Directed Energy Directorate	**Core Researcher, Integrated Experiments.** Key member of the experimental team for integrated liner-on-plasma tests.	Integrated FRCHX experiments; FRC lifetime studies [9]

This team, particularly Dr. Degnan, brought a deep, pre-existing knowledge base in solid liner implosion physics to the collaboration.[18] This expertise was foundational to the program, providing the high-power compression capability that LANL lacked. However, the publication record of this team during the FRCHX era is dominated by papers on integrated experiments and the persistent FRC lifetime issue, with no specific publications detailing dedicated research into MRT mitigation for the MTF application.[29]

3. Final Assessment

The synthesis of the preceding analysis provides a definitive, confidence-scored conclusion regarding the maturity of MRT mitigation strategies within the LANL-AFRL MTF program as of 2013.

The evidence converges on a single, coherent picture: the LANL/AFRL collaboration's primary programmatic focus was solving the FRC target lifetime problem, which was a necessary precondition for any meaningful compression heating experiment. LANL's world-class MRT simulation and diagnostic capabilities were not applied to the FRCHX program because resources were directed at the more immediate FRC stability issue. Similarly, AFRL's role was to provide a mature liner implosion capability, not to conduct new R&D into MRT mitigation techniques within the scope of the FRCHX project.

Maturity Assessment (Circa 2013):
The maturity of MRT mitigation strategies specifically developed for and tested on the FRCHX platform is assessed as Technology Readiness Level (TRL) 1-2 (Basic principles observed/Technology concept formulated). This low TRL reflects the fact that while the MRT instability was recognized as a critical future challenge for the MTF concept, it had not yet become the subject of dedicated, systematic experimental or computational investigation

within the program itself.
Confidence Score: HIGH. This assessment is based on strong, convergent evidence from the program's own publications, which overwhelmingly emphasize the FRC lifetime problem, and the conspicuous absence of publications on FRCHX-specific MRT mitigation. This absence is particularly telling given the vibrant research landscape on the topic in adjacent HEDP programs like MagLIF, indicating a deliberate and logical prioritization of effort within the FRCHX program.

Determination of Prototype Readiness:
The research circa 2013 did not indicate that MRT mitigation strategies were sufficiently advanced to enable a successful, stable implosion in an operational MTF prototype. The program had not yet reliably demonstrated a stable, long-lived plasma target that could survive until the point of maximum liner compression. Without a viable target, the question of the liner's stability during the subsequent compression phase, while critically important, remained a future research challenge. The MTF concept, as pursued in FRCHX, was still in the basic science phase of validating its core components and had not yet earned the technical right to address the complex, integrated physics of liner stability in a fusion context.

Works cited

1. Measurements of Magneto-Rayleigh-Taylor Instability Growth during the Implosion of Initially Solid Al Tubes Driven by the 20-MA, 100-ns Z Facility | Phys. Rev. Lett. - Physical Review Link Manager, accessed August 24, 2025, https://link.aps.org/doi/10.1103/PhysRevLett.105.185001
2. Measurements of Magneto-Rayleigh-Taylor Instability Growth during the Implosion of Initially Solid Al Tubes Driven by - Semantic Scholar, accessed August 24, 2025, https://pdfs.semanticscholar.org/8b83/aee32cadc2eb502f7a238a6bdcd7e963fc61.pdf
3. Rayleigh-Taylor Instability - Center for Nonlinear Studies, accessed August 24, 2025, https://cnls.lanl.gov/External/people/highlights/Ramaprabhu_2pager.pdf
4. Direct Numerical Simulations of Rayleigh-Taylor instability - Los Alamos National Laboratory, accessed August 24, 2025, https://public.lanl.gov/livescu/frames/Livescu_etal_JPHYS11.pdf
5. Deceleration-stage Rayleigh-Taylor growth in a background magnetic field studied in cylindrical and Cartesian geometries, accessed August 24, 2025, https://laro.lanl.gov/view/pdfCoverPage?instCode=01LANL_INST&filePid=13158284050003761&download=true
6. A two-dimensional numerical study of the magneto-Rayleigh–Taylor ..., accessed August 24, 2025, https://pubs.aip.org/aip/pop/article/32/3/033901/3338751/A-two-dimensional-numerical-study-of-the-magneto
7. Magneto-Rayleigh-Taylor Instability: Theory and Simulation in Planar and Cylindrical Pulsed Power Targets. - Deep Blue Repositories, accessed August 24, 2025, https://deepblue.lib.umich.edu/handle/2027.42/113414

8. Temporal evolution of surface ripples on a finite plasma slab subject to the magneto-Rayleigh-Taylor instability, accessed August 24, 2025, http://plasmabay.engin.umich.edu/wp-content/uploads/sites/281/2021/08/Weis-2014-Temporal-evolution-of-surface-ripples-on-a-finite-plasma-slab-subject-to-the-magneto-Rayleigh-Taylor-instability.pdf
9. Increased_FRC_lifetimes_using_a_longer_t.pdf
10. FRCHX Magnetized Target Fusion HEDLP Experiments - Scientific, technical publications in the nuclear field | IAEA, accessed August 24, 2025, https://www-pub.iaea.org/mtcd/meetings/fec2008/ic_p4-13.pdf
11. Status of Fusion Energy Science Research at Los Alamos - FIRE, accessed August 24, 2025, https://fire.pppl.gov/fpa10_LANL_Wurden.pdf
12. Using Richtmyer-Meshkov Instabilities to Estimate Metal Strength at Very High Rates - Los Alamos National Laboratory, accessed August 24, 2025, https://public.lanl.gov/prime/SEM15_RMI_preprint.pdf
13. Design of a high-resolution Rayleigh-Taylor experiment with the Crystal Backlighter Imager on the National Ignition Facility (Journal Article) - OSTI, accessed August 24, 2025, https://www.osti.gov/pages/biblio/1867095
14. FRX-L: A Plasma Injector for Magnetized Target Fusion, accessed August 24, 2025, https://fusionenergy.lanl.gov/Documents/FRX-L-Flyer.pdf
15. P hysics Division R esearch R eview - Los Alamos Fusion Energy Sciences, accessed August 24, 2025, https://fusionenergy.lanl.gov/Documents/FRX-L-Flyer-ver2.pdf
16. FRC Compression Heating Experiment (FRCHX) at AFRL - DTIC, accessed August 24, 2025, https://apps.dtic.mil/sti/tr/pdf/ADA610349.pdf
17. Magnetized target fusion - Wikipedia, accessed August 24, 2025, https://en.wikipedia.org/wiki/Magnetized_target_fusion
18. Measurements of Solid Liner Implosion for Magnetized Target Fusion - OSTI, accessed August 24, 2025, https://www.osti.gov/etdeweb/servlets/purl/20261460
19. (PDF) Magneto-Rayleigh-Taylor instability and feedthrough in a resistive liquid-metal liner of a finite thickness - ResearchGate, accessed August 24, 2025, https://www.researchgate.net/publication/381770830_Magneto-Rayleigh-Taylor_instability_and_feedthrough_in_a_resistive_liquid-metal_liner_of_a_finite_thickness
20. Mitigation of magneto-Rayleigh-Taylor instability growth in a triple ..., accessed August 24, 2025, https://link.aps.org/doi/10.1103/PhysRevE.104.L023201
21. DE-SC0012328 - Public Abstract | PAMS, accessed August 24, 2025, https://pamspublic.science.energy.gov/WebPAMSExternal/Interface/Common/ViewPublicAbstract.aspx?rv=5125bb1b-3184-4e6c-af4d-501c6957b271&rtc=24&PRoleId=10
22. Effects of magnetic shear on magneto-Rayleigh-Taylor instability - Plasma, Beams, and Interface Science Group, accessed August 24, 2025, https://pbi.engin.umich.edu/wp-content/uploads/sites/678/2024/10/MRT2012.pdf
23. Numerical study of implosion instability mitigation in magnetically driven solid liner dynamic screw pinches - Bohrium, accessed August 24, 2025, https://www.bohrium.com/paper-details/numerical-study-of-implosion-instability

-mitigation-in-magnetically-driven-solid-liner-dynamic-screw-pinches/977515724748619968-551
24. Stabilization of Liner Implosions via a Dynamic Screw Pinch - ResearchGate, accessed August 24, 2025, https://www.researchgate.net/publication/342995212_Stabilization_of_Liner_Implosions_via_a_Dynamic_Screw_Pinch
25. Electrothermal Instability Mitigation by Using Thick Dielectric Coatings on Magnetically Imploded Conductors | Phys. Rev. Lett. - Physical Review Link Manager, accessed August 24, 2025, https://link.aps.org/doi/10.1103/PhysRevLett.112.135002
26. Experimental Studies of Instability Development in Magnetically Driven Systems - OSTI.GOV, accessed August 24, 2025, https://www.osti.gov/servlets/purl/1427216
27. Experimental and Computational Progress on Liner Implosions for Compression of FRCs, accessed August 24, 2025, https://www.researchgate.net/publication/3168297_Experimental_and_Computational_Progress_on_Liner_Implosions_for_Compression_of_FRCs
28. Technique for fabrication of ultrathin foils in cylindrical geometry for liner-plasma implosion experiments with sub-megaampere currents - OSTI, accessed August 24, 2025, https://www.osti.gov/servlets/purl/1229753
29. Chris Grabowski Senior Researcher at United States Air Force Research Laboratory, accessed August 24, 2025, https://www.researchgate.net/profile/Chris-Grabowski
30. (PDF) Electromagnetic Implosion of Spherical Liner - ResearchGate, accessed August 24, 2025, https://www.researchgate.net/publication/13232167_Electromagnetic_Implosion_of_Spherical_Liner
31. Simulations of Imploding Solid Liner Melting and Vaporization vs Liner Thickness, and Evidence for "Melt Waves" - DTIC, accessed August 24, 2025, https://apps.dtic.mil/sti/tr/pdf/ADA635971.pdf
32. Edward RUDEN | Doctor of Philosophy | United States Air Force ..., accessed August 24, 2025, https://www.researchgate.net/profile/Edward-Ruden
33. (PDF) Rotation of electrothermal-instability-driven overheating structure due to helically oriented surface magnetic field on a high-current-density aluminum rod - ResearchGate, accessed August 24, 2025, https://www.researchgate.net/publication/394407765_Rotation_of_electrothermal-instability-driven_overheating_structure_due_to_helically_oriented_surface_magnetic_field_on_a_high-current-density_aluminum_rod
34. Phys. Rev. E 105, 025206 (2022) - Magnetized ablative Rayleigh-Taylor instability in three dimensions, accessed August 24, 2025, https://link.aps.org/doi/10.1103/PhysRevE.105.025206
35. Growth rate of the turbulent magnetic Rayleigh-Taylor instability | Phys. Rev. E, accessed August 24, 2025, https://link.aps.org/doi/10.1103/PhysRevE.106.065201
36. Bell-Plesset effects in Rayleigh-Taylor instability of finite ... - Bohrium, accessed August 24, 2025, https://www.bohrium.com/paper-details/bell-plesset-effects-in-rayleigh-taylor-in

stability-of-finite-thickness-spherical-and-cylindrical-shells/814567959753129986-551
37. Numerical and experimental efforts to explain delayed gas breakdown in ?-pinch devices with bias magnetic field, accessed August 24, 2025, https://eplab.ae.illinois.edu/Publications/AIAA-2012-3929.pdf
38. FRC Compression Heating Experiment (FRCHX) at AFRL - DTIC, accessed August 24, 2025, https://apps.dtic.mil/sti/html/tr/ADA610349/
39. FRC COMPRESSION HEATING EXPERIMENT (CHX) AT AFRL - Los Alamos National Laboratory, accessed August 24, 2025, https://laro.lanl.gov/esploro/outputs/conferenceProceeding/FRC-COMPRESSION-HEATING-EXPERIMENT-CHX-AT/9916364429303761
40. FRC compression heating experiment (FRCHX) at AFRL | Request, accessed August 24, 2025, https://www.researchgate.net/publication/224340951_FRC_compression_heating_experiment_FRCHX_at_AFRL
41. Addressing Short Trapped-Flux Lifetime in High-Density ... - Bohrium, accessed August 24, 2025, https://www.bohrium.com/paper-details/addressing-short-trapped-flux-lifetime-in-high-density-field-reversed-configuration-plasmas-in-frchx/813159622272614400-628
42. Electromagnetic implosion of spherical liner - PubMed, accessed August 24, 2025, https://pubmed.ncbi.nlm.nih.gov/10057708/
43. Design and Operation of High Energy Liner Implosions at 16 MA for Studies of Converging Shocks - DTIC, accessed August 24, 2025, https://apps.dtic.mil/sti/tr/pdf/ADA638593.pdf