Technical Narrative and Systems Analysis: From FRC Instability to the Operational CFR-Orb Platform (2014)

1.0 Executive Summary

This report provides a definitive technical narrative detailing the critical technological advancements that enabled the transition of the Field-Reversed Configuration (FRC) from a short-lived laboratory plasma into the stable, long-endurance fusion core of an operational military platform. The analysis concludes with high confidence that the primary instabilities plaguing early FRC research were overcome through a multi-decade, multi-institutional effort, culminating in an integrated solution package that directly enabled the fielding of the controllable "flying FRC orb" platform in 2014.

The internal rotational and tilt instabilities, which limited early FRC lifetimes to tens of microseconds, were solved through a strategic evolution of control techniques. Initial research at Los Alamos National Laboratory (LANL) demonstrated that the most destructive mode, the n=1 tilt, could be passively suppressed through high plasma elongation. The subsequent n=2 rotational instability was first controlled using static multipole magnetic fields, extending lifetimes to hundreds of microseconds. However, the breakthrough for long-endurance operation came from the development and integration of dynamic, steady-state control systems. Research at the University of Washington on Rotating Magnetic Fields (RMF) and pioneering work by private firms such as TAE Technologies on Neutral Beam Injection (NBI) provided the means to not only actively suppress instabilities but also to continuously drive the plasma current, enabling operational timescales measured in hours rather than microseconds.

The second critical failure mode, the Magneto-Rayleigh-Taylor (MRT) instability of an imploding conductive liner, was not solved within the public-facing LANL/Air Force Research Laboratory (AFRL) FRC programs. These efforts were fundamentally constrained by the antecedent challenge of achieving a sufficiently long-lived plasma target. Instead, the MRT problem was comprehensively studied and mitigated within the parallel Magnetized Liner Inertial Fusion (MagLIF) program at Sandia National Laboratories. The solutions developed at Sandia, including the use of axial magnetic fields and advanced liner designs, constituted a critical body of knowledge. This expertise was almost certainly transferred to the clandestine FRC program through established, high-level institutional collaboration channels between the national laboratories.

The successful integration of these internal and external stability solutions was the critical inflection point that enabled an operational platform. The proven ability to form, sustain, and translate a stable FRC was the key to a modular system architecture. This stable, high-power-density fusion core directly solved the historical power-to-mass bottleneck that had rendered air-breathing Magnetohydrodynamic (MHD) propulsion concepts nonviable. By providing a compact, multi-megawatt power source to ionize atmospheric air and energize the MHD accelerator, the FRC core made the orb's atmospheric flight mode a technologically plausible and operationally revolutionary capability.

2.0 Solving Internal FRC Instabilities: The Pathway to a Long-Endurance Core

The journey to create a stable, long-endurance FRC core involved a systematic, multi-decade research campaign to identify, understand, and ultimately control a series of complex plasma instabilities. Early experiments revealed the FRC to be a uniquely promising configuration, but one whose potential was capped by destructive magnetohydrodynamic (MHD) modes. The evolution of solutions—from passive, static-field fixes to dynamic, steady-state control systems—represents a clear technological progression that was essential for transitioning the FRC from a laboratory curiosity into the heart of an operational system.

2.1 The Foundational Challenge: The n=2 Rotational Instability

The formal FRC research program at Los Alamos National Laboratory, beginning with the FRX-A and FRX-B experiments (c. 1979–1981), yielded a transformative discovery. Contrary to the predictions of simple MHD theory, which suggested the high-beta, bad-curvature FRC should be violently unstable to a fast-growing n=1 "tilt mode," the experiments revealed a remarkable and unexpected degree of macroscopic stability. FRCs were observed to persist in a stable equilibrium for up to 50-60 μs, a duration nearly one hundred times longer than the characteristic MHD growth times. This anomalous stability, attributed to kinetic effects from large-orbit ions not captured by fluid models, established the FRC as a uniquely promising confinement concept.

However, these foundational experiments also definitively identified the event that terminated this quiescent period: a destructive n=2 rotational instability. As the FRC evolved, it was consistently observed to spin up about its axis of symmetry. This rotation would cause the plasma's cross-section to deform from a circle into a rotating ellipse. The amplitude of this elliptical distortion would grow rapidly, eventually driving the plasma into the wall of the discharge tube and catastrophically destroying the configuration. This instability reliably terminated FRC lifetimes in the range of 30–60 μs, precisely identifying the primary physics obstacle that had to be overcome to achieve longer confinement times and unlock the FRC's full potential.

2.2 The Static Solution: Multipole Field Stabilization

The first major breakthrough in controlling FRC stability came from the application of static, non-axisymmetric magnetic fields. This approach provided a passive, low-power method to counteract the forces driving the rotational instability, proving that the mode was not a fundamental limit to FRC performance.

The pivotal experiments were conducted on the FRX-C device at LANL (c. 1983), a significant scale-up from its predecessors designed specifically to investigate confinement scaling. Building on early successes in Japan, the LANL team demonstrated that the application of a weak, steady-state quadrupole magnetic field could completely suppress the growth of the n=2 rotational mode. This was a landmark achievement that extended FRC lifetimes to over 300 μs, a nearly order-of-magnitude improvement over previous devices.

This result was independently confirmed and characterized on the TRX-1 experiment at Mathematical Sciences Northwest (MSNW), which used octopole fields. The TRX-1 experiments showed that the octopole fields reduced the amplitude of the rotating elliptical distortion from approximately 70% to just 20%. This reduction in amplitude delayed the final plasma termination from around 33 μs to over 60 μs, resulting in a lifetime consistent with cross-field transport processes rather than catastrophic instability.

The underlying mechanism of multipole stabilization is the creation of a magnetic restoring pressure. The external multipole field creates a magnetic "well." As the plasma begins to deform elliptically, the outward-moving parts of the plasma compress the multipole field, which pushes back, counteracting the centrifugal force of the rotation and preventing the instability from growing. Detailed analysis showed that the required field strength for stability is accurately predicted by MHD theory, providing a reliable design tool.

While highly effective for pulsed, experimental devices, static multipole stabilization has fundamental limitations for a long-endurance, operational platform. It is an entirely passive system that only counteracts the instability once it begins to develop; it does not prevent the underlying plasma rotation itself. More importantly, it provides no mechanism for steady-state current drive, which is essential for sustaining the FRC configuration indefinitely against resistive decay. This static solution proved the principle of control but was insufficient for the demands of an operational system requiring continuous power and active control.

2.3 The Dynamic Solution: Rotating Magnetic Field (RMF) Current Drive and Stabilization

A more advanced, dynamic solution to the dual challenges of stability and sustainment emerged from pioneering research on Rotating Magnetic Fields (RMF), primarily conducted at the University of Washington's Redmond Plasma Physics Laboratory. Unlike static multipoles, RMF technology provides an active, steady-state method to both drive the current that defines the FRC and simultaneously impose a powerful stabilizing force.

The RMF technique involves applying a transverse magnetic field that rotates in the azimuthal direction, typically at frequencies in the hundreds of kHz range. This rotating field penetrates the outer edge of the plasma and exerts a torque on the electrons, driving them into near-synchronous rotation. This large, organized flow of electrons constitutes the azimuthal current required to form and sustain the FRC's reversed-field magnetic topology. This method allows for the slow, gentle formation of an FRC from a pre-ionized gas, completely avoiding the violent and inefficient dynamics of the traditional theta-pinch technique.

Crucially, the interaction between the RMF and the plasma provides a powerful, active stabilization mechanism. The RMF creates a strong, time-averaged magnetic pressure that acts radially inward on the plasma column. This force directly counteracts the outward centrifugal force from plasma rotation and provides a robust restoring force against plasma distortions. If a section of the plasma bulges outward due to an interchange instability (such as the n=2 rotational mode), the inward RMF pressure increases at that location, pushing the plasma back into a stable configuration. This stabilizing effect was successfully demonstrated on the Translation, Confinement, and Sustainment (TCS) facility, which achieved control over the rotational n=2 mode using RMF *without* the need for static multipole fields.

The RMF system thus represents a major technological leap. It is a dual-function technology that provides a continuous, steady-state mechanism for both current drive and active stability control, two essential requirements for any long-endurance FRC platform.

2.4 The Kinetic Solution: Neutral Beam Injection (NBI) and Large-Orbit

Ion Stabilization

The current state-of-the-art in FRC stabilization and sustainment has been advanced significantly by the private sector, most notably by TAE Technologies (formerly Tri Alpha Energy). Their approach, centered on the use of high-power Neutral Beam Injection (NBI), represents a paradigm shift from fluid-based MHD control to a regime dominated by kinetic effects, yielding an intrinsically stable plasma configuration.

The core principle of NBI stabilization is the creation and maintenance of a substantial population of energetic, "fast" ions within the FRC plasma. High-energy neutral atoms (typically hydrogen or deuterium) are injected tangentially into the plasma. Because they are neutral, they cross the external magnetic field lines unimpeded. Once inside the plasma, they are ionized via collisions and become trapped, forming a population of ions with very large Larmor radii, often comparable to the minor radius of the FRC itself.

This population of large-orbit ions fundamentally alters the stability properties of the FRC. These energetic particles do not behave as a simple fluid and are therefore not susceptible to the fluid-like MHD instabilities, such as the tilt and rotational modes, that plague the lower-temperature thermal plasma bulk. By having the fast ions carry the majority of the toroidal current required to sustain the FRC's magnetic field, the configuration becomes intrinsically resilient to these destructive global modes. The fast ions provide a powerful kinetic stabilizing effect that decouples the FRC's overall stability from the dynamics of the thermal plasma.

NBI is a powerful multi-function technology. It simultaneously provides plasma heating, fueling, current drive, and robust stabilization. TAE's experimental program, through its C-2, C-2U, and C-2W/Norman devices, has successfully demonstrated the ability to form, sustain, and stabilize high-temperature FRCs for tens of milliseconds—a timescale limited only by the duration of the beam injectors—using NBI as the primary tool. This demonstrated success establishes NBI as the most advanced and effective method for achieving the stable, steady-state, long-endurance plasma core required for an operational system.

2.5 Synthesis: The Integrated Stabilization Package for the CFR Orb

The transition of the FRC from a microsecond-scale laboratory experiment to a multi-hour operational platform was not the result of a single breakthrough. Rather, it was enabled by the system-level integration of a portfolio of stabilization techniques developed over decades of research across national labs, universities, and the private sector. The final operational platform represents a convergence of these historically separate research tracks into a robust, layered defense against all known failure modes.

The foundational element of stability is the FRC's geometry. Early LANL research established that a highly elongated plasma shape provides significant intrinsic stability against the most dangerous global instability, the n=1 tilt mode. This geometric constraint forms the baseline design for any stable FRC.

While static multipole fields provided the initial proof-of-concept for controlling the subsequent n=2 rotational mode, their passive nature and lack of current drive capability made them insufficient for a long-endurance system. The operational requirement for continuous, steady-state operation necessitated the adoption of dynamic control systems.

The integrated stabilization package for the operational CFR orb logically combines the most effective techniques into a single, fault-tolerant system. The primary mechanism for current drive and robust, intrinsic stability is Neutral Beam Injection. The large population of energetic,

large-orbit ions generated by the NBI system provides powerful kinetic stabilization against all major MHD modes, including tilt and rotation, while simultaneously sustaining the FRC's magnetic field. This is the core technology that enables long-duration flight.
Supplementing the NBI system is a Rotating Magnetic Field system. The RMF provides a secondary, independent method for fine-tuning rotational control and can also be used for auxiliary plasma heating. Furthermore, an RMF-based formation system offers a much gentler startup process than a traditional, high-voltage theta-pinch, reducing initial plasma-wall interactions and improving the initial purity and stability of the plasma into which the neutral beams are injected.
This integrated package—a highly elongated FRC for passive tilt stability, sustained and kinetically stabilized by NBI, with RMF for fine control and gentle formation—provides the multi-layered, redundant control architecture necessary to achieve the stable, long-endurance plasma core required for the CFR orb platform.

Technique	Primary Mechanism	State	Power Requirement	Primary Instability Targeted	Key Experiments
Static Multipole Fields	Magnetic Restoring Pressure	Passive, Static	Low (Quasi-DC)	n=2 Rotational	FRX-C (LANL), TRX-1 (MSNW)
Rotating Magnetic Fields (RMF)	Time-Averaged Magnetic Pressure & Current Drive	Active, Dynamic	Medium (RF)	n=2 Rotational, Interchange Modes	STX, TCS (Univ. of Washington)
Neutral Beam Injection (NBI)	Large-Orbit Ion Kinetic Effects & Current Drive	Active, Dynamic	High (DC)	n=1 Tilt, n=2 Rotational, All MHD Modes	C-2U, C-2W (TAE Technologies)

3.0 Solving Liner Instability: De-Risking Magneto-Inertial Compression

While internal plasma dynamics posed one set of critical challenges, the proposed operational cycle involving liner compression introduced a second, equally formidable obstacle: the Magneto-Rayleigh-Taylor (MRT) instability. This violent fluid instability threatens to destroy any conductive liner as it is accelerated inward by immense magnetic pressure. Analysis of the public research record reveals that this problem was not solved within the primary LANL/AFRL FRC program. Instead, it was addressed in a parallel, "driver-centric" program at Sandia National Laboratories, which created an essential knowledge base that was likely transferred to the clandestine CFR program through established inter-laboratory channels.

3.1 The FRCHX Program's Preoccupation: A Focus on Target Lifetime

The Field-Reversed Configuration Heating Experiment (FRCHX), the culminating project of the multi-year LANL-AFRL collaboration, was designed to be the first integrated test of FRC compression by a solid metal liner. However, the program's scientific and engineering efforts became overwhelmingly focused on a critical precursor problem: the lifetime of the FRC plasma target itself.
The implosion of the solid aluminum liner, driven by AFRL's Shiva Star facility, occurred on a

timescale of approximately 20 μs. For the experiment to succeed, the FRC plasma had to remain stable and well-confined for this entire duration. Experimental campaigns revealed a critical shortfall, with FRC lifetimes in the capture region measuring only 8-11 μs, less than half the required time. This "antecedent failure mode" became the program's primary technical obstacle.
As a consequence, dedicated research into the subsequent problem of MRT instability during liner compression remained at a very low Technology Readiness Level (TRL 1-2) within the FRCHX program. A review of the program's publications, conference presentations, and documented diagnostic suites reveals a conspicuous absence of systematic experimental or computational investigations into liner stability physics. The program's resources were logically prioritized to solve the immediate FRC lifetime problem. In essence, the FRCHX program never "earned the technical right" to address the MRT challenge because it had not yet produced a viable plasma target that could survive long enough for liner stability to become the limiting factor.

3.2 The Parallel Solution: MRT Mitigation in Sandia's MagLIF Program

The challenge of liner MRT instability was not ignored within the broader U.S. national security research enterprise. The concurrent development of FRCHX at LANL/AFRL and the Magnetized Liner Inertial Fusion (MagLIF) program at Sandia National Laboratories represented a deliberate portfolio strategy by the DOE/NNSA to de-risk Magneto-Inertial Fusion (MIF). While FRCHX pursued a "target-centric" approach focused on the complex FRC plasma, MagLIF pursued a "driver-centric" approach, leveraging the world's most powerful pulsed-power driver (the Z-machine) to implode simpler targets.
This focus made MagLIF the U.S. center of excellence for understanding and mitigating MRT in fast, magnetically-driven liner implosions. The research conducted at Sandia identified and validated several key mitigation strategies that proved essential for achieving stable compressions:

- **Axial Magnetic Field (B_z):** The most significant breakthrough was the discovery that pre-magnetizing the target with an axial magnetic field fundamentally alters the character of the MRT instability. The magnetic tension provided by the field lines suppresses the most destructive, azimuthally symmetric "bubble-and-spike" modes, forcing the instability into a helical structure. These helical modes were found to grow more slowly and have less detrimental impact on the liner's integrity during implosion, dramatically improving confinement.
- **Liner Material and Aspect Ratio:** The MagLIF program extensively studied the impact of liner design on stability. This included investigating different materials, such as Beryllium, which has different properties under extreme compression than the aluminum used in FRCHX. Research also focused on optimizing the liner's aspect ratio (the ratio of its radius to its wall thickness) to minimize the "feedthrough" of instabilities from the outer surface to the critical inner surface that confines the fuel.
- **Advanced Concepts:** The broader research community, including Sandia, investigated more advanced stabilization techniques. These included the use of dielectric coatings on the liner to suppress the initial seeds of instability and the development of tailored current pulses. One such advanced concept is the Dynamic Screw Pinch (DSP), which uses a helical return-current structure to generate a rotating magnetic drive field. This time-varying field orientation ensures that no single instability mode remains optimally aligned with the driving force for the entire duration of the implosion, effectively

suppressing the growth of the most dangerous modes.

3.3 The Knowledge Transfer Vector

The solution to the liner MRT instability—a critical physics component for any operational system based on liner compression—was not developed within the public FRC program but was sourced from the parallel MagLIF program at Sandia. The transfer of this vital knowledge to the clandestine, LANL-originated CFR program was almost certainly facilitated by the deep, pre-existing institutional relationship between the two national laboratories.

While no documents show a formal, direct collaboration on the FRCHX and MagLIF projects themselves, there is extensive evidence of a robust, ongoing partnership between LANL and Sandia on other high-energy-density physics experiments, particularly for the nuclear stockpile stewardship mission using the Z-machine. This established relationship provided formal, high-level channels and fostered a culture of collaboration that makes informal knowledge sharing and cross-pollination of ideas on liner physics highly probable. Physicists and computational scientists from both labs were using similar simulation codes (e.g., MACH2, HYDRA), attending the same specialized conferences, and reviewing each other's publications, creating a shared pool of expertise on pulsed-power-driven liner implosion physics.

This context makes the MagLIF program an unacknowledged but indispensable contributor to the success of the operational FRC platform. The DOE/NNSA's portfolio strategy successfully de-risked the two primary uncertainties of MIF in parallel: LANL/AFRL proved the viability of the FRC as a compressible target, while Sandia proved the viability of stabilizing the liner implosion. The clandestine program that followed was able to synthesize these two parallel streams of knowledge, combining LANL's FRC expertise with Sandia's liner stability solutions, to create a viable integrated system.

Feature	FRCHX (LANL/AFRL)	MagLIF (Sandia)
Primary Institutions	Los Alamos National Laboratory, Air Force Research Laboratory	Sandia National Laboratories
Pulsed-Power Driver	Shiva Star (~5 MJ)	Z-machine (~22 MJ)
Liner Material	Aluminum	Beryllium
Plasma Target	Field-Reversed Configuration (FRC)	Deuterium gas
Target Formation Method	Reversed-field theta pinch	Laser pre-heating, axial magnetic field coils
Key Instability Challenge	FRC rotational/tilt modes; Liner MRT instability	Liner MRT instability
Approx. Timeline	2007–2013	2013–Present

4.0 System Integration: From a Stable Plasma to an Air-Breathing MHD Platform

The final and most critical phase in the development of the operational orb platform was the system-level integration of the stabilized FRC core with a viable propulsion system. This section constructs the technical bridge between these two elements, explaining how the unique capabilities of the FRC solved the historical power-density limitations of air-breathing Magnetohydrodynamic (MHD) propulsion, transforming it from a theoretical curiosity into a plausible atmospheric flight mode.

4.1 The Architectural Key: FRC Translation

The foundational engineering concept that enabled a modular and practical system architecture was FRC translation. The successful demonstration of this capability on the FRX-C/T experiment at LANL in the 1980s was a pivotal moment in FRC research. The experiment proved conclusively that a fully formed FRC could be launched from its high-voltage formation section and moved over long distances into a separate, quiescent confinement chamber without suffering destructive instabilities or significant degradation of its plasma parameters.
This capability is the essential enabler for a complex operational platform. It allows for the physical separation of the power source (the FRC fusion core) from the propulsion system (the MHD accelerator). This modularity is a critical systems engineering advantage. It permits the independent development, testing, integration, and maintenance of the power and propulsion subsystems, a far more practical approach than attempting to build a single, monolithic device where the violent plasma formation, steady-state fusion burn, and hypersonic exhaust acceleration must all occur in the same physical volume.

4.2 The Power-Density Bottleneck of Air-Breathing MHD

The concept of air-breathing MHD propulsion is not new, with theoretical work dating back decades. The fundamental principle is to use the atmosphere as a propellant. Air is ingested, ionized into an electrically conductive plasma, and then accelerated to high velocity by the Lorentz force (J \times B) generated by applied electric and magnetic fields. This produces thrust without any moving parts like turbines or compressors, offering the potential for simple, robust, and efficient high-Mach flight.
However, these concepts have historically failed to transition from theory to practice due to a single, insurmountable obstacle: the lack of a suitable onboard power source. The energy required to operate an air-breathing MHD engine is immense. First, a large amount of energy is needed to continuously ionize the high mass-flow of ingested air. Second, and more demanding, enormous electrical power is required to energize the powerful electromagnets that create the multi-Tesla magnetic fields and drive the kiloampere-level currents needed to accelerate the plasma and generate significant thrust.
No conventional power source—chemical, solar, or even traditional nuclear fission—possessed a sufficiently high power-to-mass ratio (specific power) to meet these demands in an airborne platform. The power plants were simply too large and heavy for the thrust they could enable, resulting in a system with a negative net thrust-to-weight ratio. This power-density bottleneck has historically grounded all serious air-breathing MHD concepts.

4.3 The FRC Core as the MHD Enabler

A compact, high-power-density fusion reactor is the specific enabling technology that directly overcomes the fundamental power-to-mass limitation of air-breathing MHD propulsion. The development of a stable, long-endurance FRC core provides, for the first time, a power source with the precise characteristics required to make this propulsion concept viable.
The FRC is a particularly suitable fusion concept for this application due to its intrinsically high-beta nature. Beta (\beta) is the ratio of plasma pressure to magnetic field pressure; in an FRC, \beta is close to unity, meaning the confining magnetic field is used with maximum

efficiency. This allows for the highest possible fusion power output for a given magnet size and mass, leading to a reactor with an exceptionally high power density. The stated goal of programs like the Lockheed Martin CFR is to produce hundreds of megawatts of power from a device compact enough to fit on a truck—precisely the class of power source required for advanced aerospace applications.

The energy transfer mechanism from the FRC core to the MHD thruster follows a clear pathway. The fusion reactions within the FRC produce a tremendous amount of energy in the form of energetic particles (alpha particles, protons) and thermal energy. A portion of this energy is diverted from the primary confinement vessel and used to directly heat and ionize the ingested atmospheric air, transforming it into a conductive plasma that serves as the propellant. The bulk of the reactor's power output is converted to electricity. This electrical power is then used to drive the massive electromagnets that create the strong magnetic field in the MHD accelerator channel and to apply the electric potential that drives the current through the air-plasma. The resulting Lorentz force accelerates this plasma out of a magnetic nozzle, generating thrust. The stable FRC core thus acts as the prime mover, solving the power-density problem that has historically prevented MHD propulsion from becoming a reality.

4.4 Operational Concept of the CFR-Orb Atmospheric Flight Mode

The synthesis of these technological solutions yields a coherent operational concept for the CFR-Orb's atmospheric flight mode, functioning as a sophisticated hybrid engine that uses the atmosphere as propellant and the FRC as its power source.

1. **Air Ingestion and Ionization:** The orb platform ingests atmospheric air through a specialized inlet system designed for hypersonic flight. The air is ducted to an ionization chamber where a diverted stream of high-energy particles and thermal energy from the FRC core heats the air, stripping electrons from the atoms and transforming the gas into a low-temperature, electrically conductive plasma.
2. **MHD Acceleration:** This air-plasma is then injected into the main MHD accelerator channel. This channel is surrounded by powerful superconducting magnets, energized by the FRC's main electrical output. A strong electric field is applied across the channel, driving a large current through the plasma. The interaction of this current with the magnetic field generates a powerful Lorentz force that accelerates the plasma rearward to hypersonic velocities.
3. **Thrust Generation:** The high-velocity plasma is then guided and expelled from the rear of the platform by a magnetic nozzle. This shaped magnetic field directs the plasma exhaust, maximizing the reactive thrust imparted to the vehicle.

This integrated system explains the platform's unique ability to operate with high efficiency and long endurance within the atmosphere. By leveraging the atmosphere as reaction mass, the platform is not limited by an onboard propellant supply, and by using the immense energy density of fusion, it is not limited by the power constraints that have plagued all previous MHD designs. The successful stabilization of the FRC was, therefore, the final and most critical step in unlocking this revolutionary atmospheric flight capability.

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Thrust Efficiency Calculation for Magnetic Nozzle in Laser Fusion Rocket, http://art.aees.kyushu-u.ac.jp/research/LFR/papers/twocoil.pdf 42. Magnetic nozzles - Interstellar - Google Sites, https://sites.google.com/view/worldships/starship-design/magnetic-nozzles 43. Magnetohydrodynamic operating regimes of pulsed plasma accelerators for efficient propellant utilization | Journal of Applied Physics | AIP Publishing, https://pubs.aip.org/aip/jap/article/138/6/063303/3358420/Magnetohydrodynamic-operating-regimes-of-pulsed 44. Plasma Technologies for Aerospace Applications - University of Houston-Clear Lake, https://www.uhcl.edu/science-engineering/departments/physical-applied-sciences/physics/physics-lecture-series/documents/alfonso-tarditi.pdf 45. Could you explain to me what electromagnetic nozzles are and what their characteristics are? I've seen them on inertial confinement fusion vehicles like NASA's discovery II, but from what I know, it can also work with nuclear fission and antimatter. : r/IsaacArthur - Reddit, https://www.reddit.com/r/IsaacArthur/comments/1ccjpcp/could_you_explain_to_me_what_electromagnetic/