

The Fusion Driven Rocket

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Abstract— A very persuasive reason for investigating the applicability of nuclear power in rockets is the vast energy density gain of nuclear fuel when compared to chemical combustion energy. The Fusion Driven rocket (FDR) represents a new approach to fusion propulsion where the power source releases its energy directly into the propellant, not requiring conversion to electricity. It employs a solid lithium propellant that requires no significant tankage mass. The propellant is rapidly heated and accelerated to high exhaust velocity (> 30 km/s), while having no substantial physical interaction with the spacecraft thereby avoiding damage to the rocket as well as limiting the thermal heat load and therefor radiator mass. The FDR concept is based on research conducted at MSNW and the University of Washington on magnetically driven implosions of thin metal bands onto magnetized plasmoids to achieve nuclear fusion. Here, Lithium bands are inductively driven to converge radially and axially forming a thick blanket surrounding the plasmoid. Virtually all of the radiant, neutron and particle energy from the fusion plasma is absorbed by the encapsulating shell thus isolating the thruster and spacecraft from the intense energy release. This energy, in addition to the powerful Ohmic heating in the shell at peak magnetic field compression, is adequate to vaporize and ionize the Lithium. The expansion of this hot, ionized metal propellant is inhibited from blow-back onto the thruster as it is produced inside the large region filled with a divergent axial magnetic field. The propellant thermal energy is consequently converted into high thrust at an optimal Isp through this magnetic nozzle. The back emf from magnetic flux compression due to the expanding Lithium plasma can be utilized to resupply the electrical energy needed for subsequent pulses. This paper outlines these key elements of the FDR concept and the state of their current development. These include: 1) The results from laboratory testing of the metal band compression with sufficient imploded foil kinetic energy (~ 0.5 MJ) to reach conditions required for fusion breakeven conditions. (2) The results from both a 1D code for analyzing the magnetically driven metal band implosion dynamics as well as a full 3D ANSYS® calculation of the implosion dynamics. (3) Based on these results the FDR spacecraft design and mass budget were formulated. (4) A range of mission architectures for which FDR would be enabling, including a rapid, single launch manned Mars mission were developed and are described.

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1. INTRODUCTION

The future of manned space exploration and development of space depends critically on the creation of a dramatically more efficient propulsion system for in-space transportation. This has been recognized for many years. A very persuasive reason for investigating the applicability of nuclear power for these missions is the vast energy density gain of nuclear fuel when compared to chemical combustion energy. The combustion of Hydrogen and Oxygen has an energy release of 13 MJ/kg, whereas the fission of ^{235}U yields approximately 8×10^7 MJ/kg and the fusion of Deuterium and Tritium has a 3.6×10^8 MJ/kg yield. So far, the use of fission energy represents the nearest term application of nuclear power for propulsion. Several fission-based propulsion schemes have been proposed for in-space transportation such as the Nuclear Thermal Rocket (NTR) [1]. In the NTR a cooling fluid or propellant is passed through a core of material that has been heated by fission. This makes the NTR effectively a heated gas rocket. With the present limitations of materials, NTR gas temperatures cannot exceed chemical propulsion gas temperatures. The use of Hydrogen provides for an increase in Isp to 900 s. With $\Delta V \sim 9$ km/sec the propellant mass is reduced by an order of magnitude for a given spacecraft mass. Unfortunately, this is considerably offset by increased spacecraft mass (payload, structure, shielding, tankage etc.). A significant mass is required for the low mass density propellant (H_2) as the specific gravity of liquid Hydrogen is around 0.07, compared to 0.95 for an $\text{O}_2\text{-H}_2$ chemical engine. The net result then is a propulsion system that is better than chemical, but not enough to really be a “game changer”. Proposed Nuclear Electric Propulsion (NEP) systems employ high Isp thrusters like the Ion and Hall thrusters which solve the propellant Isp issue. The problem for NEP is the inherent inefficiency of the electrical power generation. Shedding the excess reactor heat requires an enormous radiator mass. The large reactor and power conversion masses just add to this problem making for too low a specific power (ratio of jet power to system mass) for rapid space transportation.

Invoking nuclear fusion for space propulsion, at least as it has been envisioned up till now, does not significantly alter this picture as it has been developed primarily as an alternate source for electrical grid power. This endeavor is far from completion, and even if nuclear fusion were to be eventually developed for terrestrial power generation, the resulting power plant would be unlikely to have any role in space propulsion for all the same reasons that trouble NEP - but worse. Past efforts in this regard have all come to be dismissed, and rightfully so, primarily for the following two reasons. The first has been alluded to already. The propulsion system is reactor based. The straightforward application of a reactor-based fusion-electric system creates a colossal mass and heat rejection problem for space application. In a detailed analysis for the most compact tokamak concept, the spherical torus, spacecraft masses of 4000 metric tons (t) were projected [2]. The maximum launch mass would need to be less than 150 t if current chemical rockets are used for launch to LEO. The second is the use of the fusion plasma and/or the fusion products as propellant. Due to the resultant extremely high exhaust velocities, the enormous mismatch from the optimal exhaust velocity (3-5 km/sec) leaves the spacecraft with either insufficient thrust or enormous power requirements.

An optimal solution to this dilemma would be a fusion propulsion system where (1) the power source releases its

energy directly into the propellant, not requiring conversion to electricity. (2) a solid propellant would be employed requiring no significant tankage mass. (3) The propellant would be directly heated by the plasma and fusion product and accelerated to high exhaust velocity (> 20 km/s), and where the propellant (4) has no significant physical interaction with the spacecraft thereby limiting thermal heat load, spacecraft damage, and radiator mass. The Fusion Driven Rocket (FDR) [3-5] to be detailed in this paper represents an attempt to incorporate all four of these attributes, and in so doing, lead to a practical propulsion system that is capable of taking full advantage of the promise that fusion energy represents.

2. ELUCIDATION OF THE FDR CONCEPT

The Fusion Driven Rocket (FDR) is a innovative approach to fusion propulsion where the power source releases its energy directly into the propellant, not requiring conversion to electricity. It employs a solid lithium propellant that requires no significant tankage mass. The propellant is rapidly heated and accelerated to high exhaust velocity (> 30 km/s), while having no substantial physical interaction with the spacecraft thereby avoiding damage to the rocket and limiting both the thermal heat load and radiator mass.

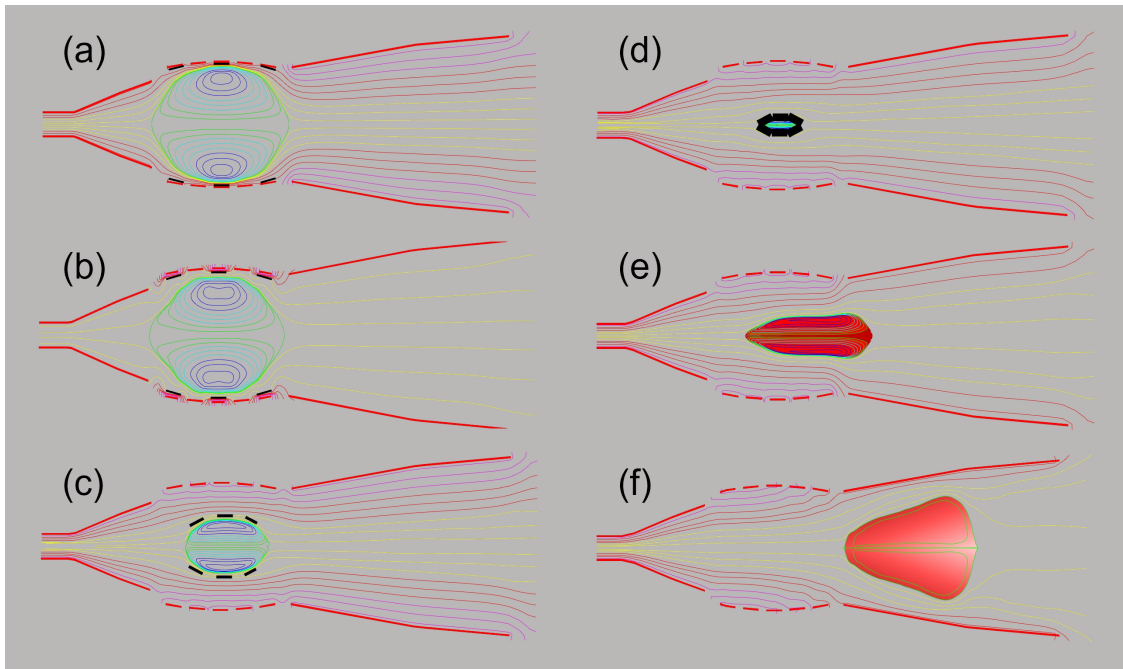


Figure 1. Cross section of the FDR illustrating the magnetic topology and steps involved in the process of generating a fusion-based propulsion system. (a) A pair of loop antennas (not shown for clarity - see Fig. 3) are employed to create a large Deuterium plasmoid inside the thruster chamber. (b) Thin Lithium metal bands inserted near the thruster wall are driven by external coils at the proper angle and speed to compress the plasmoid both axially and radially inward. (c) Plasmoid density is additionally enhanced during compression by frozen Deuterium/Tritium pellet fueling. (d) Converging Lithium bands thicken and merge to form fusion blanket compressing target FRC plasmoid to fusion ignition conditions. (e) The Lithium blanket is vaporized and ionized by the fusion plasma, radiation, fusion products, as well as direct Ohmic heating from the large currents carried in the blanket at peak compression. (f) the Lithium plasma expands in the divergent magnetic field resulting in a highly directed flow of the metal plasma out of this magnetic nozzle attaining maximum thrust and velocity.

The key to achieving the FDR stems from research at MSNW and the University of Washington on the magnetically driven implosion of metal foils, as well as techniques to create a suitable magnetized plasma target that when sufficiently compressed, can attain fusion ignition conditions. A logical extension of this work led to a method that utilized these metal bands to not only achieve fusion conditions, but to then serve as the propellant as well. In the Fusion Driven Rocket (FDR) several low-mass, Lithium metal bands are inductively driven to converge radially and axially and form a thick blanket surrounding the target plasmoid while compressing the plasmoid to fusion conditions. This process is depicted in Fig. 1. Virtually all of the radiant, and particle energy from the plasma, as well as the fusion reaction products, are absorbed by the encapsulating, thick metal blanket thereby isolating the spacecraft from the fusion process. This energy, in addition to the intense Ohmic heating of the Lithium shell at peak magnetic field compression, is more than adequate to vaporize and ionize the metal blanket. The expansion of this hot, ionized metal propellant is contained by a divergent magnetic field. This magnetically insulated nozzle provides a means to convert the thermal energy of the Lithium plasma into directed flow and thereby produce high thrust at the optimal Isp. The energy from the fusion process, along with the waste heat, can thus be utilized at very high efficiency.

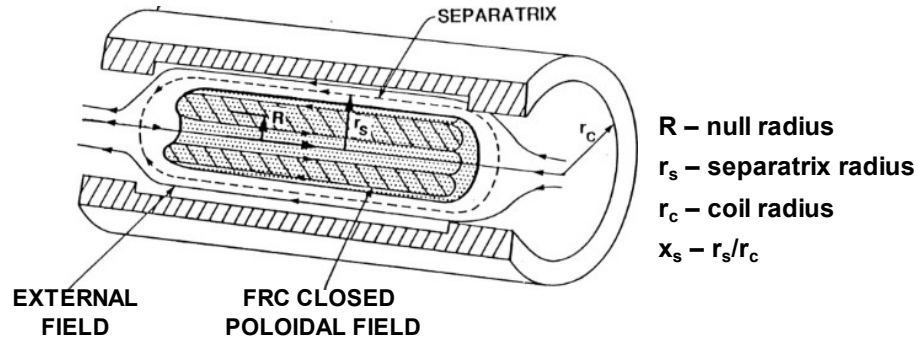
A critical element to enable fusion energy to be employed for space propulsion as embodied in the FDR is a practical method to produce a fusion plasma of the appropriate size and power, and directly channel the fusion energy into thrust at the appropriate Isp. It is believed that particulars of the concept have been ascertained and that the resultant design and expectation of performance for the FDR is supported by both theory and experiment. A thorough account of the concept is the subject of this paper, and the following is an

outline as to the presentation. A description of the physical principles of the Fusion Driven Rocket is detailed in section 3. This will be followed by the exposition of the relevant fusion physics involved. Analytic and numerical modeling have been employed in the study of both the plasma and the Lithium band dynamics during the compression and fusion burn phases. The results from 2D MHD plasma calculations and 3D ANSYS Explicit Dynamics® Solver (AEDS) simulations of the Lithium band behavior during convergence will be presented. A 1D model of the Lithium band dynamics was formulated that also included the full electrical circuit behavior involved in driving the bands to high velocity. This model was able to accurately reproduce the results from AEDS calculations making it far easier to perform parameter optimization. From this analysis, the necessary electrical and structural components were determined. An optimized point design for the FDR lithium band compression system was determined and will be discussed. The specifications for the electrical and physical systems required for the FDR are also presented. This is followed in section 4 by a summary of the results from experimental testing of several key components of the FDR process illustrated in Fig. 1.

The full FDR design was performed making sure that all key electrical elements were capable of the repetitive operation needed for a practical implementation of the FDR. Based on these results it was possible to arrive at an initial spacecraft mass budget. The paper concludes with a description of the requirements for and capabilities of the FDR in realizing a rapid manned mission to Mars in section 5.

3. PHYSICS OF THE FUSION DRIVEN ROCKET

Description of the Various Fusion Driven Rocket Stages



	$P_0 = n_0 k T = \frac{B_{ext}^2}{2\mu_0}$	Radial Pressure Balance
Equilibrium Relations:	$\langle \beta \rangle = \int_0^{r_s} \frac{2\mu_0 P}{B^2} dr = 1 - \frac{1}{2} x_s^2$	Axial Pressure Balance
	$B_{ext} = \frac{B_{vac}}{(1 - x_s^2)}$	Flux conservation

Figure 2. The Field Reversed Configuration (FRC) and key equilibrium relations.

As mentioned, space-based fusion demands a much lower system power and mass than those now being considered for Earth-based conventional power plants. The lowest mass system by which a fusion plasma can be efficiently achieved, and the one to be employed here, is based on the simply connected, very compact, high energy density Field Reversed Configuration plasmoid or FRC [6-8] (see Fig. 2). It is of paramount advantage to employ a simply connected, closed field line plasma (plasmoid) that has intrinsically high β (plasma/magnetic pressure ratio), so that when compressed one can achieve the relatively small-scale fusion yield (~ 10 s of megawatts) desired for space propulsion. Most importantly, the FRC has already demonstrated in past experiments the confinement scaling with size and density required to assure sufficient lifetime to survive the time required to achieve the relatively large wall compression ratio of the target FRC plasmoid envisioned here [9]. A large compression ratio is advantageous for several reasons as will be discussed. The entire FDR process that is illustrated in Fig.1 can be broken down into several phases that will now be described.

First Phase - FRC formation (Fig.1 a)—Start with an initial large-scale coil and plasmoid which permits the use of a high efficiency coil driver for coupling to the Lithium bands as it is easier to minimize stray inductance and resistance with a large coil. It also provides for “stand-off”, i.e., the ability to isolate and protect the necessary entry ports for fueling, as well as the thruster body walls from any deleterious effects from the resultant fusion energy release. And finally, since FRC plasma lifetime scales as r^2 [6], whereas the time to compress scales as r , sufficiently large initial scale assures a

target implosion site with the coil driver both physically and electrically isolated from the fusion propulsion process. The driver energy coupling efficiency can be as high as 90% as the coil driver is typically the inductive element of a simple oscillating circuit where resistive circuit losses are a small fraction of the energy transferred.

Initially, a rather small axial magnetic field is required to confine the FRC within the Li bands (~ 0.05 T). But with the large compression ratio provided by the convergent flux-preserving Li bands, this trapped axial magnetic field will increase to over 500 T at peak compression. As will be seen, this field is more than sufficient to compress the FRC to ignition and produce substantial fusion energy gain.

A Rotating Magnetic Field (RMF) is employed to generate the FRC. This technique has been employed in several past FRC experiments [10-12], and at nearly the scale to be employed here [11,12]. A depiction of the key elements of the RMF FRC formation method can be found in Fig. 3. Experimentally it has been found that The FRC lifetime scales as the FRC poloidal flux which is generated by the RMF azimuthally driven currents. An FRC radius of roughly 0.75 m is sufficient to provide enough flux for an FRC plasma lifetime several times the compression timescale of roughly 0.4 msec assuming a Lithium band inward velocity of ~ 2 km/sec. This is well within the range of velocities that have been attained experimentally with Aluminum bands of greater mass [13]. It is also the speed predicted by the 1D code as well as the 3D ANSYS calculations for Lithium bands at this scale and mass for achieving fusion gain.

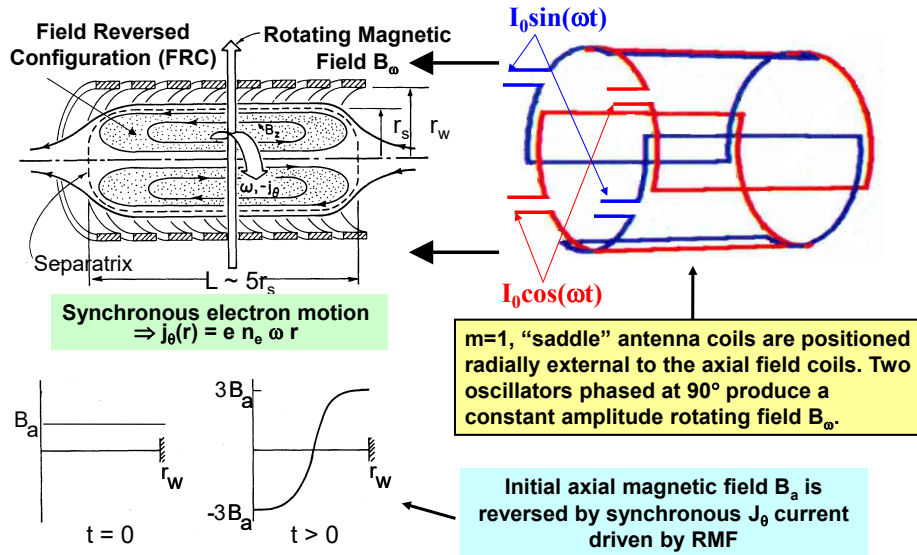


Figure. 3. Key elements for the generation of an FRC with a Rotating Magnetic Field (RMF)

viable, magnetized fusion plasma after compression. At large scale the Lithium bands can be closely coupled to the driver coils even when the coils are placed external to the thruster chamber. Assuming the use of a dielectric chamber wall, the convergent band motion can be inductively driven. In this way the metal bands can be positioned up to a meter from the

Phase 2 - Lithium band compression (Fig. 1 b-d)—The next phase is the inductive acceleration of the Lithium bands by the external coil drivers. The bank energy requirements for attaining the necessary convergence speed and mass will be discussed in the next subsection. As the bands begin to accelerate, pellets consisting of a combination of frozen

Deuterium (^2H), Tritium (^3H) are injected radially through small ports located at the chamber boundary into the FRC field null region at the characteristic inward velocity of the bands. As exotic as this may sound, it is a common technique employed in Tokamak experiments for plasma refueling, as well as confinement improvement due to the fact that the plasma energy confinement scales with the density [14,15]. While the FRC confinement also scales with the density [11], the purpose here is to bring the FRC density up to the proper extent to achieve the optimal ion temperature for ignition prior to full compression ($T_i \sim 10$ keV). It is expected that having the pellet comoving and thus being ionized at the FRC field null will cause a significant increase in both particle as well as flux confinement.

With inductive drive it is possible to induce an axial convergence of the metal bands in numerous ways. Several methods have been devised and tested to achieve metal band axial convergence from as simple as a small axial displacement of the metal band from being directly centered under the driver coil, as was done in the experiments, to a tapered coil and metal band as illustrated in Figs. 1 and 4. The AEDS code has been found to give accurate representation of the metal band physics in 3D. This also provides a check for the metal band dynamic motion described by a simple 1D model through the acceleration phase [16]. In the calculation shown in Fig. 4, the bands are seen to buckle as they collapse inward. This is to be expected due to their initial, extremely large radius/thickness ratio that can be greater than 500 to 1 for the prototype FDR bands. The buckling mode number is

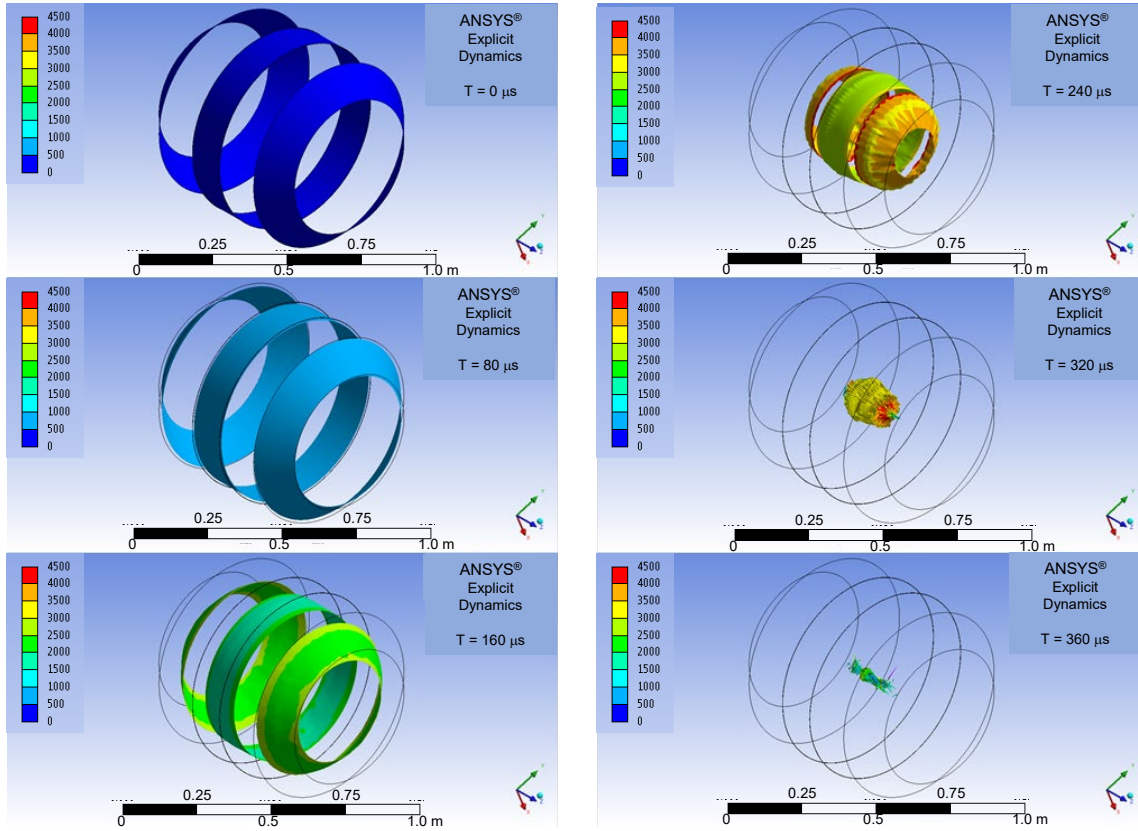


Figure 4. AEDS calculation of the 3D behavior of three Aluminum metal bands driven to converge similar to that desired for the compression of an FRC to fusion ignition conditions.

During the compression phase the Lithium metal bands move radially and axially inward to create a three-dimensional compression of the target FRC. The initial acceleration phase ends when the band radius has been reduced by about 20% since the inductive coupling rapidly decreases as the distance from the thruster wall increases. The bands continue to move in and compress the inner magnetic field and FRC at roughly a constant speed due to the bands' large inertial momentum. The behavior of the bands' response to the magnetic pressure and subsequent motion has been calculated with the ANSYS Explicit Dynamics Software (AEDS) and a prototypical calculation is shown in Fig. 4.

also seen to be quite high, but with the distortion amplitude relatively small. While it was experimentally observed to not be particularly deleterious to the magnetic field compression process, it was found that by pleating the bands azimuthally at roughly the observed mode number allowed for the bands to fold in symmetrically and avoid any nonuniformities and internal stresses that would otherwise arise during the final stages of the compression (see Fig. 5). This also provided a simple means for insertion of the bands via an inlet slot at the upstream end of the thruster body. By partially pre-folding the bands, the bands could be brought in and easily positioned

under the driver coils where they could then be extended into place directly under the driver coils.

There are several reasons not to leave the potential buckling to underlying imperfections or lack of azimuthal symmetry when it would be only slightly more effort to form the metal bands with the locations for folding preset. This “pleating” will assure a symmetric folding as the metal bands converge radially inward with the minimal internal stress buildup. This stress can lead to a significant slowing of the bands as they converge and thicken. It does not occur when the band folds are made so that the depth of the pleat is set so that the bands collapse and come into contact forming a solid configuration desired at peak compression. This not only minimizes the internal energy losses, it reduces the tendency to bounce back at peak compression due to the built up internal stresses. Most importantly, it provides for a much more uniform inner, plasma-facing surface, and thereby avoids protrusions that could inject Lithium or create plasma jets during the eventual melting and vaporization/ionization once the fusion process is initiated.

less than the dwell time of the Lithium shell which provides for a large fusion gain.

The azimuthal currents induced in the Lithium shell by this field reach 15 MA rapidly melting the inner surface. This raises the possible issue of band instability with regard to Rayleigh-Taylor (RT) modes during the deceleration and reversal that accompanies the magnetic compression and inner wall rebound. While a liquid inner wall may make for a more uniform and stress-free surface, as well as a better conducting surface, it is unstable to RT. However, it was shown by Turchi et al. [17] that rotation of the fluid can completely stabilize these modes. Adding rotational momentum to the bands sufficient to accomplish this is actually not that difficult. As with the Rotating Magnetic Field (RMF) FRC formation method illustrated in Fig. 3, a second set of saddle coils can be added external to the thruster chamber that produces a rotating magnetic field inside the thruster chamber (see Fig. 3). However here the rotational frequency, and thus energy for RT stabilization, is quite modest. It should be noted that the bands are free to rotate

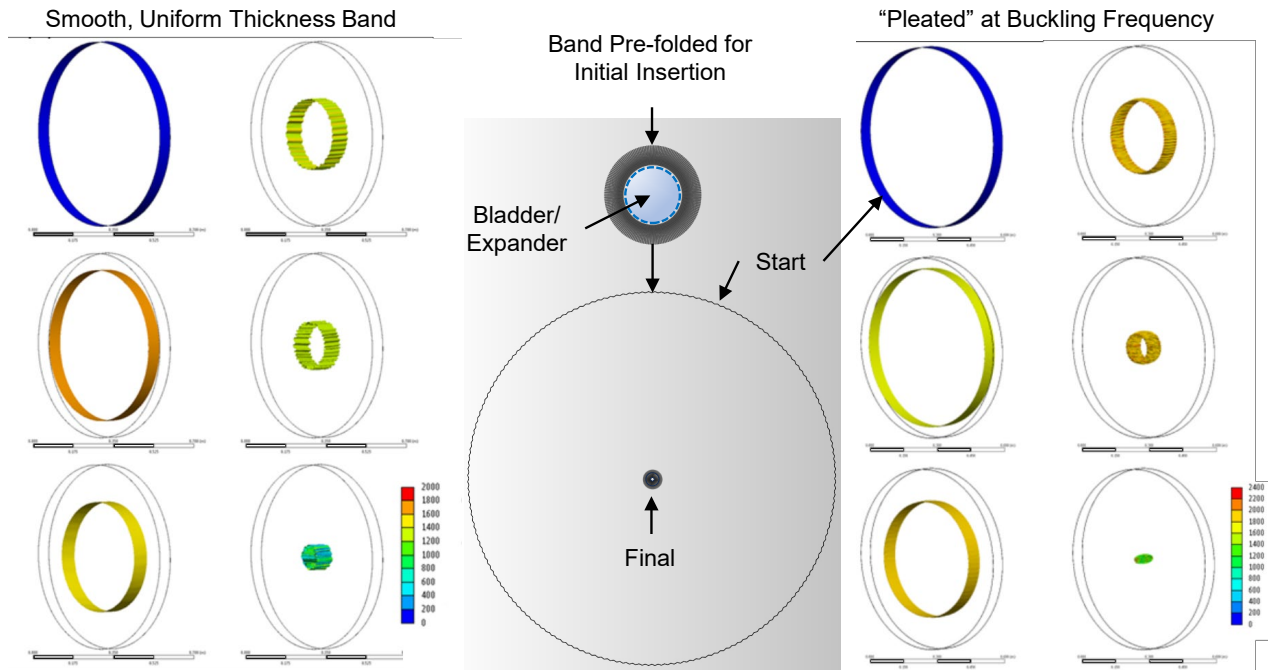


Figure 5. ANSYS® AEDS 3D calculations of a thin metal band implosion with (right) and without pleating. Central section CAD drawings illustrate the process of insertion, start of the implosion and final state with a pleated metal band. The slower implosion for the unpleated band is due energy loss due to bending and internal stresses.

Phase 3 - Fusion ignition (Fig 1. d- e)—The next phase is the fusion burn. From the 1D calculations matched to the AEDS calculations for the prototype FDR, it was found that at peak compression the bands collapse to form a thick shell around the FRC with an outer radius, $r_{out} \sim 5$ cm. This shell acts as a fusion blanket that absorbs a large fraction of the fusion energy as well as the radiated plasma energy during the brief fusion burn time. The inner radius, r_{in} , has reached a minimum radius of 6.3 mm at a peak magnetic field of 528 T. The equilibrium FRC plasma pressure is thus 1.1×10^{11} Pa or 1.1 Megabar. The time to ignition at this pressure is much

once they have been driven inward away from contact with the outer wall. In order to apply an azimuthal torque to the Li bands a radial magnetic field must be coupled into the bands from the external coils. The rotation can be induced by simply imbedding a slowly rotating transverse magnetic field into the bands prior to implosion. The best method for achieving this is to embed a quadrupole field. An example of the field line structure from a set of axial current rods placed radially outside the driver coils is shown in Fig. 6. The 100 kHz range frequencies used for generating electron current flow to form the FRC is screened from penetrating inside the bands. Magnetic field penetration and coupling to the bands is no

real issue for the band rotational stabilization. The thinness of the bands and more importantly, the large ratio of initial to final Li band radius requires a very slow initial rotational velocity to be induced to be sufficient for stabilization at the small radius where the melting will occur. It was determined [17] that the stability condition for the fluid could be stated as:

$$\Omega_0^2 \geq \frac{2}{5\mu_0} \frac{r_i^2 B_i^2}{\rho_{Li} r_{Li}^4 \ln(r_{Li}/r_i)} \quad (1)$$

$$\Omega_i \geq 58.1 \text{ rad/sec} \quad (\Omega_L \geq 0.46 \text{ rad/sec})$$

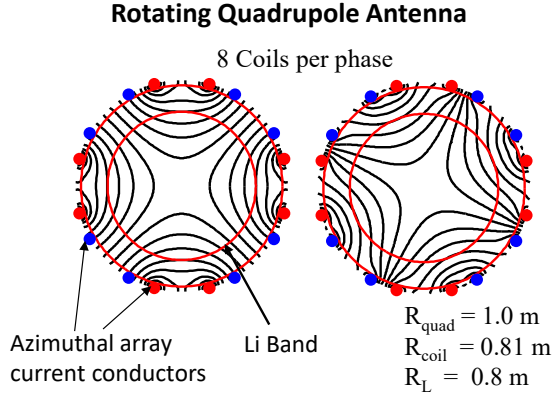


Figure 6. Two-phase coil configuration for inducing Li band rotation with a rotating quadrupole magnetic field.

The second line reflects the values anticipated for the Li band inner radius at field at peak magnetic field compression ($B_i = 528 \text{ T}$, $r_i = 6.3 \text{ mm}$) where the initial band radius, $r_{Li} = 0.8 \text{ m}$, reflects the appropriate scale discussed for the full-scale FDR. The density of Lithium, ρ_{Li} , is 543 kg/m^3 . The rotational energy that must be acquired by the band is negligible compared to the total band kinetic energy. From force calculations on the prototype Lithium bands, the rotating quadrupole radial magnetic field strength need be no greater than tens of gauss.

FRC rotational stability can also be an issue during the band compression time. This same quadrupole field has been employed in many FRC experiments in the past⁹ for stabilization of FRC rotational modes as well as centering the FRC, and should work in a similar manner here as these fields will remain frozen into the band wall for the relatively short duration of the band compression.

Phase 4 – Conversion of shell energy into propulsion (Fig. 1 e-f)—The final phase is the subsequent behavior of the superheated shell as it is vaporized and ionized by the magnetic field induced ohmic heating, FRC plasma, radiation, and fusion energy deposition. The response is to expand but inside the divergent magnetic field of the thruster nozzle, which allows for free expansion axially, but restricts radial motion. Here the thermal energy of this overwhelmingly Lithium plasma ($\sim 0.5 \text{ kg}$ of Lithium compared to $\sim 2 \text{ milligrams}$ of FRC Hydrogenic plasma) is

converted into directed propulsive thrust much like a conventional nozzle, but with the crucial difference being the “nozzle” is a divergent magnetic field that performs the function of thermal to directional energy conversion while providing isolation from the thruster wall which protects it from heating and erosion by the energetic Lithium plasma.

It should be possible to also derive the electrical energy required for the RMF FRC generation and implosion coil driver system from the back emf experienced by the conical magnetic field coil circuit due to the nozzle flux compression from the expanding plasma. As will be discussed, the circuitry required is not complex. It was found however that the power required for recharging the energy storage modules ($< 270 \text{ kW}$) for the metal band driver coils could readily be obtained from conventional solar electric power. For very rapid, high-power missions, the flux compressor/generator option could be adopted.

Analytic and Numerical Analysis of the FDR

Analysis of the metal band implosion was carried out for both the subscale validation experiments performed at the University of Washington (UW) and MSNW, as well as what would be required for a full-scale FDR prototype. For the purposes of the analysis given here, an estimate of the metal band kinetic energy that can be achieved is based on both modeling as well as what other inductive metal band compression experiments in the past have attained [18,19]. The dynamics of the metal band implosion are governed by the equation:

$$M_L \frac{d^2 r}{dt^2} = \left(\frac{B_{in}^2}{2\mu_0} - \frac{B_e^2}{2\mu_0} \right) 2\pi r w, \quad (2)$$

where M_L is the metal band mass, and w the Li band width. During the rapid band acceleration, very little flux can diffuse through the Li metal band (i.e. $B_{in} \ll B_e$). Due to the inertia of a solid metal band, it is possible to sustain the magnetic field pressure (i.e. maintain a constant amplitude B_e) during this time by continually increasing the flux in the gap between the coil and metal band to counter the increasing gap cross-sectional area as the metal band moves inward. This occurs naturally for a simple L-C discharge circuit with an appropriately large capacitance. The near constant magnetic field during this time is observed experimentally and was confirmed by 3D modeling with the Maxwell[®] 3D electromagnetic code. With this approximation Eq. (2) is readily integrated to obtain the metal band velocity v_L . B_e , is then determined by the stored capacitor energy minus metal band kinetic energy, E_L . The fraction of the stored energy, E_s , ($= \frac{1}{2} CV_e^2$) into the driving magnetic field energy, E_B , is characterized by an efficiency k_{eff} . By employing a circuit design with low stray inductance, E_B will be concentrated primarily in the annular gap volume between the metal bands and the driving coils. One can thus derive an expression for the compression magnetic field during the short distance Δr over which the main metal band acceleration is produced:

$$E_B = \frac{B_e^2}{2\mu_0} 2\pi r_{Li} \Delta r w = k_{eff} \frac{1}{2} C V_C^2 \Rightarrow$$

$$B_e = 5.4 \times 10^{-4} \left(\frac{C}{w} \right)^{1/2} \frac{k_{eff} V_C}{r_{Li}}, \quad (3)$$

where B_e can be expressed as a function of the initial metal band physical dimensions and circuit parameters. Here r_{Li} is the band initial radius. The radial distance over which the compression field remains large as the metal band moves inward, i.e. Δr , was taken to be equal to $r_L/5$. This approximation was obtained from both experimental results and analytical circuit calculations. Equating the remaining stored energy with the metal band kinetic energy (Ohmic losses in the metal band and coil are calculated to be negligible here), one has then for the metal band velocity:

$$v_{Li} = \left(\frac{C}{\pi r_{Li} w \delta \rho_m} \right)^{1/2} \frac{V_C}{2} \quad (4)$$

where the metal band mass, $M_L = 2\pi r_L \cdot w \cdot \delta \cdot \rho_m$ with δ being the band thickness, and ρ_m the density of the band material.

The key process of the dynamical behavior of the convergent aluminum foil metal bands was analyzed by both a one-dimensional analytic model that contains all of the relevant electrical circuit equations to provide for the calculation of the metal band motion and heating due to changing magnetic fluxes and fields. The most accurate accounting of the metal band dynamic behavior was obtained with the AEDS. Here the full three-dimensional non-linear behavior of the aluminum metal bands was modeled based on the magnetic pressure profile in time and space similar to that predicted by Eq. (2) and ANSYS Maxwell®. The result of a calculation with a physical setup similar in scale to the FDR subscale prototype tested in the experiments is shown in Fig. 7.

As mentioned, the FRC has been selected as the target plasmoid. There is practically no alternative plasma target to the FRC as it is the only simply connected, magnetically confined plasma that has demonstrated the configuration lifetime scaling required for the relatively slow metal band compression envisioned here. It is critical to have sufficient plasma confinement in order to retain plasma energy and inventory during the time required for the metal band to reach peak compression. Even for the fastest implosion speeds achieved experimentally to date (~ 3 mm/ μ s), the time to maximum compression is several times the axial ion transit time. The FRC also has the distinct feature that even with a metal band capable of only a 2D radial compression, the FRC will undergo an axial contraction due to the internal field line tension within the FRC, with the net result being effectively a 2.4D compression of the FRC. The energy within the FRC separatrix at peak compression is dominated by plasma energy that is in pressure balance with the edge magnetic field B_i inside the Li shell. The kinetic energy of the Li band is converted into the FRC thermal energy by compression as the Li bands converge. At stagnation of the collapsed bands the kinetic energy of the Li bands is converted into

compressional heating of the FRC and surrounding magnetic

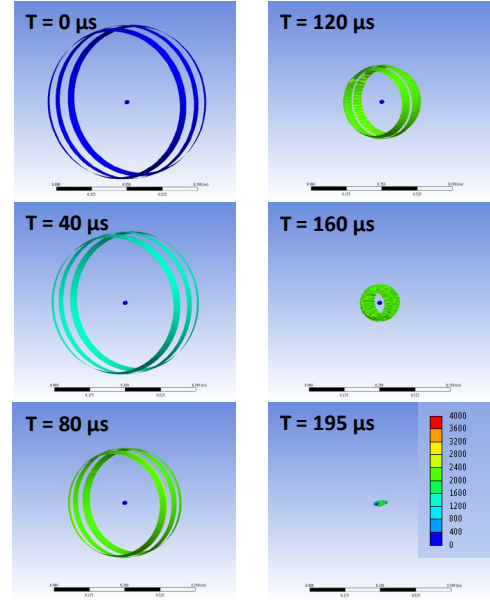


Figure 7. ANSYS Multiphysics® 3D Calculation of the convergent implosion of three bands - 0.4 m radius, 5 cm wide, 0.2 mm thick Aluminum.

field inside the shell. This allows one to write:

$$E_{Li} = \frac{1}{2} M_{Li} v_{Li}^2 = 3n_i k T_i \cdot \frac{4}{3} \pi r_i^3 \varepsilon = \frac{B_i^2}{\mu_0} \pi r_i^3 \varepsilon, \quad (5)$$

where the “i” subscript indicates values at the inner shell wall at peak compression. The plasma volume is given by $4/3\pi r_i^3 \varepsilon$ where ε is the elongation of the FRC ($l_i/2r_i$). The last expression in Eq. (5) reflects the reasonable assumption that $r_{FRC} \sim r_i$ and that the FRC plasma is in radial pressure balance with the magnetic pressure from the thin layer of axial magnetic field surrounding the FRC, i.e. $2n_i k T_i = B_i^2/2\mu_0$. One has then for the fusion energy produced in the FRC during the shell’s dwell time τ_D at peak compression:

$$E_{fus}(DT) \cong 2.82 \times 10^{-12} n_i^2 \langle \sigma v \rangle \frac{4}{3} \pi r_i^3 \varepsilon \tau_D$$

$$= 2.6 \times 10^{-41} n_i^2 T_i^2 (eV) r_i^3 \varepsilon \frac{r_o}{v_{Li}} \quad (6)$$

where n_0 and T_i are the FRC peak density and temperature. The Li shell dwell time at peak compression, τ_D , is approximated as $\sim 2r_o/v_{Li}$, the time it would take the Li bands to reach the axis unimpeded and rebound to r_o , the outer radius of the shell at peak compression. The dwell time is based on the fact that while the radial motion of the inner surface of the shell has been halted by the back pressure from the plasma and magnetic field, the outer shell surface continues to compress inward until the stagnation of the inner shell surface reaches the outer surface. The time can be much longer than the time for the inner wall to respond if it were still a thin band and the thick shell inertial mass could be ignored. As will be seen, the outer radius can be over ten

times the inner radius of the shell at peak compression. The usual approximation for the D-T fusion cross section in the optimum temperature range (5-40 keV) can be approximated within 10% by $\langle\sigma v\rangle \cong 1.1 \times 10^{-30} T^2$ (eV) [20], which was also assumed in the second equality of Eq. (6). Radial pressure balance, together with equations (5) and (6) yields a scaling for the fusion gain:

$$G = \frac{E_{fus}}{E_{Li}} = 16.0 B_i^2 \frac{r_o}{v_{Li}} \quad (7)$$

In order to obtain the most accurate values for final compression magnetic field, B_i , and the maximum Li band velocity, v_{Li} achieved; a more detailed and encompassing analysis of the implosion process must be made. This was accomplished with a 1D code that included all of the relevant physics and electrical circuitry for calculating the values of these two critical parameters. The shell outer radius, r_o can be accurately predicted in the 1D model for a single band, but the final radius depends on the axial motion of the full set of Li bands. There is considerable advantage in having a converging set of bands as indicated in Fig. 4. It provides for a full 3D compression of the FRC plasma thereby achieving a plasma that almost completely fills the interior space of the shell at the highest possible β (ratio of plasma to magnetic energy density). As this is a 3D effect, the correction to account for the increased shell radius relied on the ANSYS calculations. Nominally the 3-band convergence increased the single band radius by a factor of two. It also increased the axial length by a lesser amount. This is important in calculating the energy absorption from the fusion neutrons.

1D Lithium band model—In order to optimize the Li band driver system for the design of the FDR, a model that captures the key physics of the inductively driven band compression process was created. At the same time, for the optimization of the initial design of the FDR, a relatively fast code is required in order to run numerous design points to conduct a comparative study on the optimum design of the FDR driver. For these reasons, the driver system for the FDR is approximated as a pseudo-2D model, with coupled physics of the driver circuit, the driver internal magnetic field, the band dynamics, and the band thermal calculations. In the pseudo-2D model of the IDLC driver system, coupled 0D and 1D calculations are carried out with geometric correction factors to capture some of the important effects of the 2D and 3D physics of the band compression in order to conduct system optimization studies. The electromagnetic solver (ANSYS Maxwell 3D® Eddy Current Solver) was used to obtain the driver system inductance at various band positions. The time dependent resistivity of the driver system is determined during the execution of the code to ensure global energy conservation between the coupled solvers.

The thermal calculation for the band heating is calculated as a lumped parameter 0D system. However, the corrections due to skin-depth effects are captured in the calculations of the band heating by considering band mass that is only within the two skin-depth thickness away from the band inner surface. The thermal calculation is conducted using the heated mass

within the two skin-depth thickness to capture the skin effect in this pulsed device. Through thermal calculation, the effect of the time dependent resistivity of the band metal is also captured in the model. Further details of the code can be found elsewhere [16].

Initial Values	
Driver Coil Radius	0.80 m,
Initial Li band Radius	0.79 m
Li band thickness	1.5 mm
Initial band Temperature	80 °K
Initial band flux	0.1 Wb
Initial band internal B_i	5.0 mT
Driver cap. C	0.5 mF
Driver Volt. ΔV	60 kV
Termination	
completed in	25725 cycles
Collapse Time:	412.3 usec
Time to $B_i > B_o$	216.8 usec
Final Flux inside	0.105 Wb
Final B_i	528.1 T
Peak Li Band v_{Li}	2,065 m/s
Final r_i inside shell	6.27 mm
Final shell r_o	48.5 mm
η_{eff} (Li band $E_k / \Delta E_{driver}$)	90.2 %
Final shell Temp:	208.01 °K

Figure 8. Optimized 1D code starting conditions and final results for fusion gain in the FDR.

The driver circuit parameters and design of the Li band driver system was then optimized by running a parametric analysis using the 1D code, that integrated the behavior of the driver

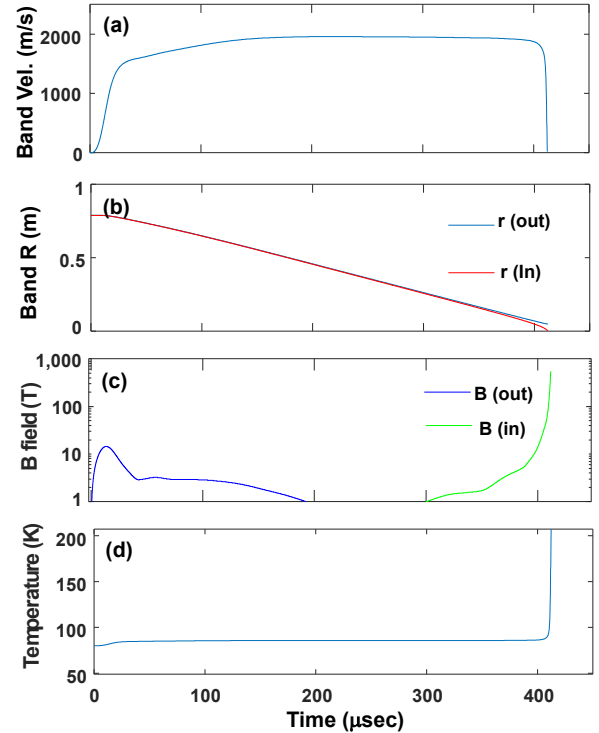


Figure 9. Various parameters from optimized Lithium band compression for prototype FDR.

circuit based on past experimental performance of such circuits. It also incorporated 3D magnetic field effects from the Maxwell analysis, Joule heating, and Li band dynamics for a single band system. A summary of the various parameters assumed for the starting conditions and some key results from the 1D Li band code for the optimized design point can be found in Fig. 8. Plots of key parameters as a function of time can be found in Figs. 9 and 10. As can be seen in Fig. 9a, the bands are rapidly accelerated near the driving coil and less so even though the magnetic field is maintained by continued flux addition (Fig. 9c). From the summary in Fig. 8 the internal flux inside the band remains essentially constant during the band drive as well as the implosion indicating that the Li band is an excellent flux conserver on this timescale. The internal magnetic field confining and the FRC does not rise significantly until near the end of the compression at small radius. It was assumed that the Li band was initially at a relatively low temperature (Fig. 9d) as it is stored external to the thruster in open space before insertion.

It is difficult on the scale of the initial Li band to get a clear sense of the behavior of the band and magnetic fields at a small radius in Fig. 9. The results for the key fusion related parameters at the critical time of maximum compression can be found in Fig. 10.

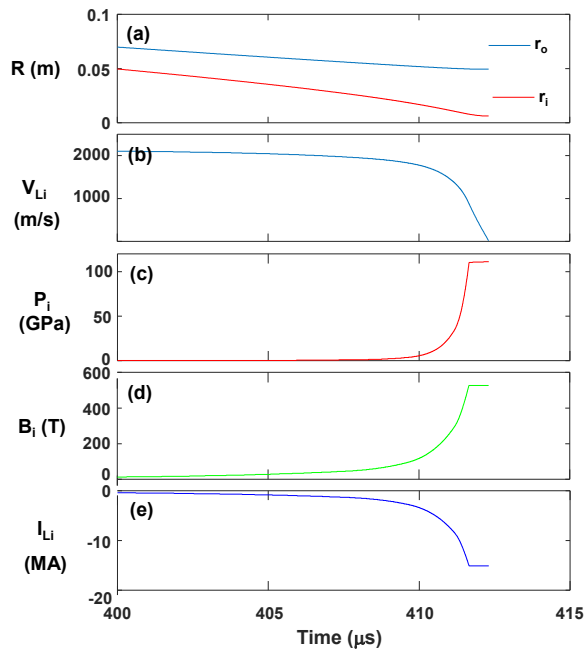


Figure 10. Key fusion parameters at the time of maximum FRC plasma compression.

4. FDR EXPERIMENTAL TESTING

Previous Experiments

The greatest challenge for the FDR concept is demonstrating the feasibility of inductively-driven, metal band compression of the FRC plasma to fusion ignition. In past experiments [11,12] it has been shown that the RMF FRC plasma can be

generated at the scale and with the confinement necessary to satisfy the FDR requirements laid out in the previous section. Other FRC experiments [21] have shown that a translating FRC can be effectively “wall-compressed” to smaller scale at high temperatures, albeit not to the extent desired here. This left metal band compression to be demonstrated at the relevant scale and energy to meet the conditions needed for the FDR. Experimental investigation of this aspect of the challenge was undertaken at the Plasma Dynamics Laboratory (PDL) at the University of Washington (UW). The results from these experiments will be presented, but first a short discussion of past efforts in this area is worthwhile.

The feasibility of rapidly accelerating inward and compressing thin hoops of aluminum and copper inductively was first demonstrated by Cnare [22] in the early 1960s. Since then, the technique has been employed in several experiments to obtain very high magnetic fields in a small volume, which is clearly a result that is highly desired here as well. Inductively driven bands have been used to obtain the largest non-explosively driven magnetic fields of up to 720 T [23]. As the analysis presented in the previous section indicated (see Eq. 7), a field of this strength would be more than sufficient to achieve substantial fusion gain with the FRC plasma.

As mentioned earlier, there are many advantages inherent in the inductively driven metal band compression of the FRC such as large stand-off from debris, electrical and physical isolation from the target, and magnetic insulation of the driver system from high energy particles to mention a few of the most important ones. Another significant advantage is operational simplicity. The solid propellant is inserted into the thruster mechanically. The plasma is created by external

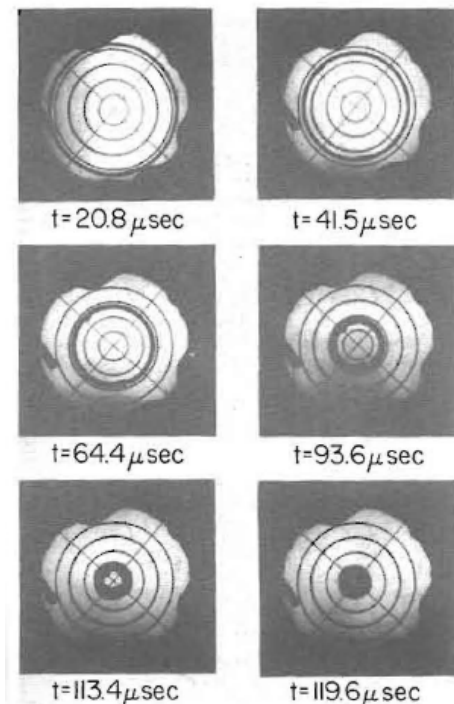


Figure 11. Sequence of images of a backlit aluminum band implosion (from Ref. [24]).

oscillating coils and then compressed to fusion conditions using a simple L-C circuit to energize the external, hoop-shaped driver coils. The rest of the sequence to high power propulsion is accomplished by the steady, conically divergent, magnetic nozzle which converts essentially all the Lithium plasma energy delivered from the fusion processes, as well as all the energy delivered by the plasma formation and Li band drivers into thrust at high Isp, as will be discussed in more detail in section 5.

After the groundbreaking experiments performed by Cnare [22], an inductively driven band similar to those employed in the experiments at the UW PDL, was realized in experiments by Turchi et al. [24] at NRL (see Fig. 11) in the early 70s. Large compression ratio convergence ($\sim 30:1$) was obtained employing a thin (1 mm), large diameter (30 cm), and axially short (7 cm) aluminum band. Peak magnetic fields as large as 140 T were achieved with excellent symmetry and quality. As was noted earlier in the Cnare experiments as well as later experiments, there is a rapidly diminishing band acceleration after the band has moved inward roughly 20% of the coil radius. This is due to the drop-off in magnetic field rise and thus force as the volume that must be filled with field grows ever greater as the band moves away from the driver coil. This limits the effective radial distance over which it is possible to efficiently maintain significant magnetic pressure. The “stroke length” however can be significantly increased by increasing the radius of the driver coil and band. By increasing the initial band radius, the distance over which one has to accelerate the bands to a given velocity increases. This in turn allows for a significantly lower axial magnetic field to be employed to achieve the same final band velocity. With the band’s increased circumferential length, the total mass accelerated by the same axial field coil is significantly increased as is the band kinetic energy.

Inductively Driven Metal Bands at Large Scale for FDR

Driving a band with a radius as envisioned here for an FDR prototype has never been demonstrated, let alone an array of bands. This demonstration therefore became the first order of business in the FDR concept validation. The initial band tests were conducted at a scale somewhat less than desired for a full-scale FDR with the coil diameter of 0.84 m. The test scale was primarily driven by two factors – cost and availability. The facility at the UW was equipped with a high voltage (up to ± 25 kV) capacitor bank with a stored energy as large as 1.0 MJ. A vacuum system and support structure for dielectric vacuum cylinders up to 0.82 m diameter was available from past large scale FRC experiments [9]. The cost to replace these elements with something larger was not only cost prohibitive, but given uncertainty as to the fate of the equipment from the band implosions, a more conservative approach was taken. For the initial band implosion experiments only a fraction of this bank was employed (870 μF at ± 15 kV for a total stored energy of 392 kJ) to avoid significant collateral damage in the early testing. It was also decided to employ only a radial force to the bands as this would spare both diagnostic ports and pumps in the end regions of the vacuum system from the post implosion, high-

velocity, metal plasma impingement anticipated. Rather than use existing fused silica tubes, a 0.8 m ID, G-10 tube was purchased for the dielectric vacuum chamber wall for the same reasons. A picture of the experimental setup can be found in Fig. 12.

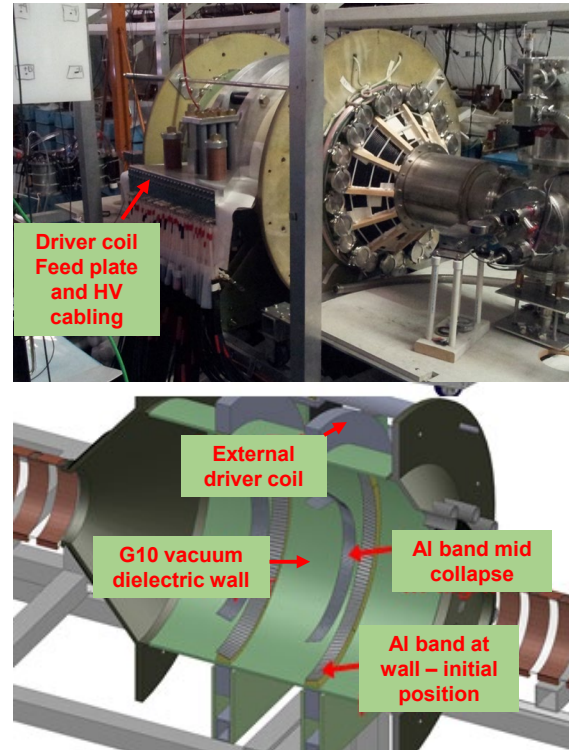


Figure 12. Large scale metal band compression test bed for FDR validation experiments at UW PDL.

The AEDS analysis for the prototype FDR with three converging bands (see Fig. 7) was based on the following. It was assumed that each band was driven by a capacitor bank with an initial energy storage of 335 kJ. The testing of one band can thus be performed at similar energy to the AEDS calculations for comparison. The first tests were conducted with 0.4 m radius aluminum bands that were 6 cm wide, and 0.4 mm thick with a resultant mass of 0.16 kg. A schematic of the FDR test bed is also shown in Fig. 12. The initial driver coils were energized by an array of 48 capacitor modules each consisting of five 25 kV 14.6 μF capacitors. A pair of D size ignitrons in series were employed for the start as well as crowbar switches. They were all triggered simultaneously by a single 25 kV hydrogen thyatron switch assuring simultaneity. The modules were divided in pairs connected in series to increase the maximum voltage (nominally ± 25 kV). The 24 module pairs were then connected in parallel to the feedplate of the driver coil via 384 high voltage coaxial cables to minimize the stray inductance (0.07 μH), which was roughly 5% that of the vacuum coil inductance (1.4 μH). The energy coupling efficiency is strongly dependent on having the band as close as possible to the coil at startup. The Aluminum band, however, acts to shunt most of the coil inductance before the band moves inward. Making the stray as small as possible is critical to maintaining the magnetic energy in the gap during band acceleration. In fact, it is

important that the stray inductance is still small compared to the inductance of the shunted coil. To a good approximation the initial coil-band system appears as an electrical stripline whose inductance is determined by the band width w (6 cm), coil-band gap distance δ_{gap} (1.3 cm), and band circumference, i.e. $L_{\text{gap}} (\mu\text{H}) \sim (2\pi r_c) \cdot \delta_{\text{gap}} / w \sim 0.56 \mu\text{H}$.

The prototype-scale band convergence tests were performed with aluminum bands in the G-10 vacuum chamber with a driver coil pair as illustrated in Fig. 12. The bands were fabricated from Aluminum 1100 alloy strip that was lap seam welded together and annealed. The weld was ground to maintain as best as possible the thickness, thermal and resistive properties of the bulk material. This was not ideal as the band mass at the weld was considerably higher than elsewhere. As will be discussed, this led to a slower inward velocity for this section of the band. The bands were placed inside the vacuum chamber as indicated in Fig. 12. While the vacuum wall increases the gap considerably from what would be employed in a space-based driver, it was necessary here to avoid issues with atmospheric interference, and would have been required in any case for future RMF FRC plasmoid formation, and band compression experiments.

The principal diagnostics that were employed to determine band position as a function of time were several internal magnetic probes on axis, as well as external axial flux and B loops. End-on images of the band motion were also obtained with a backlit fast framing camera as in the Cnare and Turchi experiments. These images yield detailed information regarding band uniformity during convergence. In order to avoid confusion, a single band was installed and only one coil energized for the end-on imaging. The resultant images from

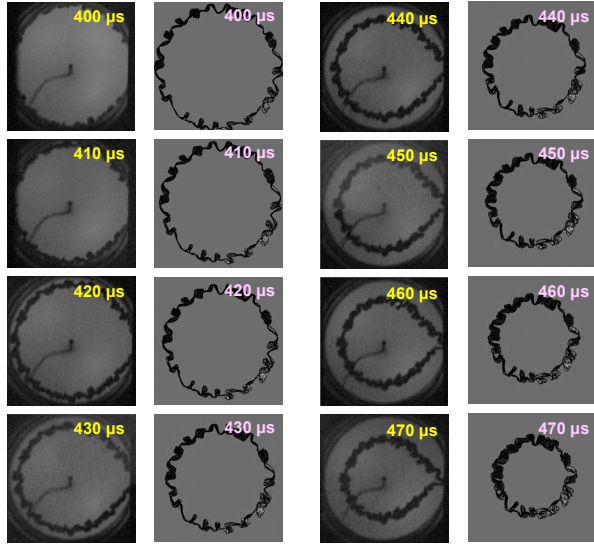


Figure 13. Experimental End-on images (left) and AEDS code results (right) for a 0.4 m radius, 0.16 kg aluminum band. The stored energy was 175 kJ (± 10 kV, 870 μF). The time refers to discharge initiation. Aperture in experimental images is at 14 cm radius. Internal probe wires can also be seen on axis.

the experiment as well as similar constructed “images” obtained from the 3D AEDS calculation are shown in Fig. 13. It should be noted that these images were obtained for only the final 14 cm of the band’s radially inward travel as the vacuum chamber end cones (see Fig. 12) blocked visual access at large radius. The buckling seen in both experiment and calculations occurs fairly early in the implosion. As was discussed earlier, this early buckling serves a useful function in that it minimizes the energy lost to compressional internal energy in the bands as the bands move inward. With pleating, which was not used here for simplicity, the buckles would naturally merge uniformly together to form a thick, compact stable wall at peak compression as desired.

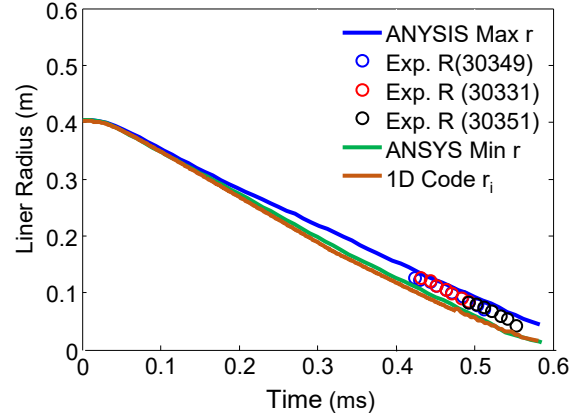


Figure 14. Comparison of experimental results with both the 3D AEDS and 1D numerical code predictions.

The AEDS calculations were carried out with the same material, dimensions, and magnetic pressure time history as the bands. The predicted band velocity and the actual band velocity were quite close as can be seen in Fig. 14. The near identical results validate the use of both the AEDS code for accurately predicting band dynamics and the 1D band code in determining the interplay between the driving circuit and band energy and dynamics. Both will be employed in designing future band implosion geometries and driver electrical systems.

As mentioned, not all of the band was observed to converge uniformly in the experiment as Fig 13 shows quite clearly. The band section near the feedplate is retarded as it did not achieve the same inward velocity as the rest of the band. This problem was accentuated by the thick aluminum feed plates causing the return magnetic field outside the coil to divert azimuthally around them near the feedplate gap, and unfortunately where the weld was positioned. This significantly lowered the field in the gap at that location. Remarkably, this “tardy” section the band did not appear to cause any major issues until it was sectioned off late in the implosion. The feedplate does not need to be a thick conductor as all the coil current flows in the first few skin depths (~ 1 mm) of the inner wall. A redesigned thin (7 mm) feedplate backed with G-10 (5 cm) reinforcement, as well as a less bulky seam-welded band produced band implosions that exhibited no such asymmetry.

Interestingly, and more importantly for the desired propulsion application, virtually all of the damage generated by the imploded bands was created by axial jets consisting of primarily of vaporized aluminum. Two 12-inch square by 1-inch-thick polycarbonate plates were positioned at each end of the conical sections inside the vacuum chamber (see Fig. 12) to protect the quartz viewing windows. These ended up serving as witness plates. A fairly uniform spray of Aluminum was observed alongside deep cracking and pitting. Even though the plates were positioned axially over a meter away from the implosion site, the bulk of the damage was centered on the plates and inside roughly a 10 cm radius. There was no visible damage to the vacuum wall under the driver coils or elsewhere in the chamber. The conversion of radial kinetic energy into axial kinetic energy appears to be a natural consequence of magnetized band implosions. The high energy bands were clearly rapidly heated and melted by Ohmic currents flowing in the band. As the band collapses on axis, the magnetic field increases dramatically as the axial magnetic field, which had diffused through the band during the initial acceleration, is rapidly compressed to very high values. The metal band acts to trap this field and the rapidly increasing magnetic field-induced current quickly heats, melts, and vaporizes the band as anticipated. However, without the much greater heating from the fusion event, there is little significant band ionization. The axial jet-like behavior of the aluminum vapor is thus not a result of a plasma interaction with the axial magnetic field, but a consequence of the magnetic field on the implosion physics while the band is still intact and a good conductor. Since magnetic field effects are not yet a direct part of the AEDS calculations, this process is best studied and understood using the 1D band code that includes the behavior of all the relevant fields, fluxes, Ohmic heating, and circuit behavior. But at this small, post implosion radius, the current code terminates at this point. The code will need to be enhanced to include melting and vaporization effects to further understand this phenomenon as it could make direct conversion of the fusion energy more robust requiring less magnetic insulation to avoid thruster wall interactions.

5. MISSION ANALYSIS

The first mission analysis performed for FDR was conducted performing trade studies of fusion gain band mass and trip time from Earth to Mars. Various mission scenarios were examined based on the fusion conditions derived from the 1D analysis presented earlier and validated by past experiments with inductively driven bands and consistent with the past results on RMF FRC formation and lifetime. The desire was to arrive at the optimal manned Mars missions. A list of the mission goals that were targeted to be attained by the Fusion Driven Rocket can be found in Table 1.

Achieving these goals would clearly provide for a substantial improvement over current architectures based on either chemical or fission nuclear propulsion. To this end, two of the criteria considered the most crucial for a manned Mars mission, were that being a maximum 90-day transit to Mars,

Table 1. Mission goals based of the objective of reducing transit times and mass required at LEO

Mission Architecture Goals	
1.	~ 90- & 30-day transit time to and from Mars
2.	Single launch to Mars (< 150 t IMLEO)
3.	No pre-deployed assets
4.	> 50 t Mars Payload mass
5.	Propulsive Mars Orbit Insertion (MOI)
6.	Propulsive Earth Orbit Insertion (EOI)
7.	Reusable FDR spacecraft and habitat (MTV)

and a single launch of the entire spacecraft needed for the manned Mars mission to LEO. Of the two, the 90-day transfer was considered the more imperative as it not only reduced the cost and safety risks of a manned mission to Mars, but was the simplest, and possibly the only viable way to bring radiation exposure to within permissible limits. Missions faster than 90 days are certainly feasible with FDR propulsion, and one such mission will be considered. Of course, the ΔV budget is significantly increased by the shorter transit time along with a reduced payload mass fraction, and possibly increasing initial mass in low earth orbit (IMLEO). This leads to the second main criterion which limits the IMLEO mass to 150 t or less. This is the projected payload limit for the reusable version of the SpaceX Starship launch rocket. It was felt that this was a key element in the feasibility of manned Mars missions as it greatly simplifies the total mission plan and substantially reduces mission costs. Beyond these two main mission criteria, several of the other mission goals were pursued.

Foremost was a payload mass large enough to carry the Mars Ascent/descent Vehicle (MAV). For this study the payload to Mars would be primarily a Mars Entry Vehicle of 50 t. This vehicle would consist of the entry, descent, and landing system, the surface habitat for the 50 day stay, and finally the ascent module to rendezvous with the orbiting FDR spacecraft for Earth return. Consumables were estimated to be 1.5 kg per person per day. For a crew of six on the 210-day mission this was roughly 2 t. The payload for the entire mission including the return payload to earth, would be the Mars Transfer Vehicle (MTV) weighing 15 t. It is worth noting that a Crew Exploration Vehicle (CEV) or Earth re-entry vehicle is not included in the mass budget. One of the mission assumptions was to have FDR as a reusable spacecraft. Therefore, the entire spacecraft will be in circular Earth orbit where a rendezvous with a CEV could be made. By doing so, 11 t of mass would not be needlessly transported all the way to Mars and back. The dry mass breakdown is shown in Table 2.

Table 2. Spacecraft dry mass summary including Mars payload.

System	Mass (t)
Mars Lander (MAV)	50
Crew/Consumables	2
Transit habitat (MTV)	15
FDR spacecraft	15
Total Dry Mass	82

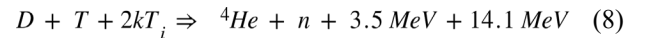
A comment about two other mission goals listed in Table 1 relating to the use of full propulsive orbit insertion maneuvers at both Mars and Earth return. Eliminating aerobraking at Mars reduces risk and complexity of the spacecraft and mission architecture. Furthermore, it was shown in earlier analysis^{13xx} that the mass of the heat shield required for an Aerobraking maneuver would actually more massive than the propellant needed by the FDR to perform the same ΔV maneuver. While chemical propulsion missions and even NTP propulsion show large mass saving by using an aerobraking shield instead of more propellant, this is not true for a high Isp engine like the FDR.

Along similar lines there is the aerocapture maneuver that is normally assumed upon Earth return. Previous analyses considered aerocapture at Earth a possibility as it is well understood based on previous flight experience. It employed return trajectories with Earth entry at speeds as high as 12 km/s. This was deemed acceptable based on the 11 km/s required for the lunar Crew Exploration Vehicle (CEV). For this case study, an Earth Orbit Insertion maneuver was conducted instead of relying on a direct entry approach from Mars. This was done for two reasons. First, it allows for the standard CEV to be used without necessitating the development of higher density, lightweight, thermal protection systems. Second, by allowing the spacecraft to enter into an earth orbit upon return from Mars, the FDR spacecraft would be ready for future missions simply by re-launching a new payload and additional propellant. As mentioned, the FDR spacecraft is designed as a reusable system.

It is important to note that the use of ISRU for ascent propellant would be a valuable way to increase the MAV crew and scale, as well as adding a more extensive Surface Habitat (SHAB). Sending a fully fueled MAV to Mars is assumed here for simplicity. If not employing ISRU, both the MAV and the SHAB could be sent to Mars 2 years before the launch of the crew. The SHAB would land at the target site while the MAV would loiter in orbit awaiting crew arrival over 2 years later. The crew members would then ride the MAV to the surface and be assured that they had a fully fueled ascent vehicle that is capable of ascending back to the spacecraft. Again, this approach is not part of the first order design, but would be something for further consideration in future analyses.

FDR projected fusion gain and jet power—It is important at this point to discuss a critical aspect of the FDR concept in order to construct mission scenarios with some fidelity. This is the subject of the expected fusion gain. An expression for the gain was derived and is stated in Eq. (7). If one uses the values derived from the 1D calculation of a single Lithium band (see Fig. 8), one arrives at $G = 105$. The actual operation of the FDR band implosion scheme employs at least three bands, which is not something the 1D code could handle as the other two bands are launched so as to axial converge and with the central band compress to form the compact Lithium blanket or shell. To understand the implication with regard to gain of the three converging band case, the AEDS 3D code was used to model this type of interaction. The result from the 3D analysis shows roughly a doubling of the outer radius, r_o , of the shell. As it cannot directly capture the compression effects of the additional bands on the internal magnetic field B_i , the effect must be evaluated through an analytic analysis. This is actually a fairly straight forward task. From Eq. (5) it can be seen that increasing the band energy E_{Li} by three will increase the total band thus magnetic energy proportionately. Particle conservation during this rapid compression phase requires product of density and internal volume to remain constant. Thus, the volume part of the last expression ($\pi r_o^3 \epsilon$) in Eq. (5) must scale like $1/n_o$. For an adiabatic compression, which is certainly the case here (band speed $\ll$ ion thermal speed), $n \sim B^{6/5}$. Thus, the increase in B_i going from one to three bands would be $3^{4/5} = 2.41$. From Eq. (7) then the total gain for the three bands would be $G = (2) \cdot (2.41)^2 \cdot (105) = 1,218$! This of course is unrealistic. The intense fusion heating that would result would certainly cause a tremendous surge in pressure that would violate several assumptions about inertial containment and shell integrity during the fusion process.

There is actually a fundamental limit as to what the gain can be in a closed, non-refuellable system such as this. It is sometimes referred to as a “batch burn” as the fuel source is limited to what is trapped in the Lithium shell. One can only produce so many fusions before all the D and T ions have been consumed to form alphas (^4He) and neutrons. In addition, one must consider the fact that the fusion event causes a loss in thermal energy along with the D and T ions. Consider the reaction equation including the energy sources and sinks:



Where the thermal energy of the fusing ions ranges from roughly 10 to 40 keV during the fusion burn process. The initial temperature will be rapidly increased during the fusion burn phase being driven by the alpha heating. This means that the effective range for fusion gain during this time is:

$$G_{eff} = \frac{17.6 \text{ MeV}}{2kT_i}, \text{ or } 880 < G_{eff} < 220 \quad (9)$$

As the fusion cross section monotonically increases with ion temperature over this range, the realized gain will be closer to the higher range. A more conservative fusion gain of 300

will thus be assumed for purposes of the Mars mission analysis. There is one more point to be made here. From Eq. (7) the relation between the fusion energy gained by the Lithium shell to the kinetic energy of the bands also determines the Li propellant exhaust velocity as:

$$\begin{aligned} E_{jet} &= f_c E_{fus} = f_c G_{eff} E_{Li} \Rightarrow \\ \frac{1}{2} M_{Li} v_{jet}^2 &= f_c G_{eff} \frac{1}{2} M_{Li} v_{Li}^2 \Rightarrow, \\ v_{jet} &= \sqrt{f_c G_{eff}} v_{Li} = 34.0 \frac{km}{s} \end{aligned} \quad (10)$$

where f_c is the conversion efficiency from fusion thermal energy into directed energy and reflects frozen flow losses as well as plume divergence losses, both of which should be small compared to the huge fusion energy gain. A value of $f_c = 0.9$ was assumed in Eq. (10).

Along with the information provided in Table 2, and the exhaust velocity from Eq. (10) it is necessary to pick a pulse repetition rate in order to specify the jet power in order to determine the burn time needed to perform the various ΔV maneuvers for the manned Mars mission analysis. The fusion pulse rep-rate will be set primarily by the time it takes to insert and position three new bands under the driver coils. The second most lengthy event is topping off and/or recharging the capacitor banks for the RMF and band driver circuits. Puffing in the Deuterium gas (the Tritium is injected during band compression in the frozen pellet described earlier), should take the least time. It was decided that a nominal 10 seconds was sufficient for band insertion. This could easily be doubled or tripled if needed with little consequence in propellant usage. At 10 seconds the FDR jet power is 66.5 MW. Given the large fusion energy yield per pulse (~ 600 MJ) it is worth a brief description as to how the thermal energy released by the fusion event is translated into directed energy in a manner that achieves high conversion efficiency while protecting the spacecraft from any deleterious interaction with the Lithium plasma propellant.

It is possible to simulate the plasma behavior in the divergent field of the magnetic nozzle as illustrated in Fig. 1 with the 2D resistive MHD code once the Lithium shell has been vaporized and sufficiently ionized. The calculation is initialized to be at a point early in the expansion phase of the plasma (after step 1-d but prior to step 1-e in Fig. 1). At this time the plasma is assumed to have essentially no net axial velocity and is expanding outward in the divergent nozzle magnetic field at the characteristic thermal speed of the Lithium plasma ~ 3 cm/ μ sec. In reality the plasma would have acquired some axial momentum prior to the start initial conditions of the calculation due to code constraints at small scale. The initial state reflects the Lithium plasma after assuming it has uniformly expanded out to a radius of 0.3 m. This ignores the fact that the plasma motion in the upstream direction is throttled by the MHD magnetic bottleneck formed there by the strongly convergent field while the plasma freely expands along the field in the downstream direction. Even with the code's delayed start to the plasma

acceleration, the thermal conversion occurs rapidly enough. This is due to other effects to be described next. The resistive 2D MHD analysis, at the least, provides a worse-case scenario.

A significant source of plasma acceleration stems from the highly conductive nature of the plasma on these timescales. The fusion heated Lithium plasma initially expands out in all directions, but in the transverse direction to the magnetic field it must sweep the nozzle magnetic field along with it. The result is the plasma ends up compressing the magnetic field as it is also prohibited from penetrating through the electrically conductive thruster wall. This compressional work is accomplished by giving up plasma thermal energy. The transverse motion of the plasma rapidly decreases due to both this thermal energy loss and the increasing magnetic field back pressure. There is however no such deceleration parallel to the magnetic field. In fact, the opposite occurs. With the now much larger compression magnetic field near the wall, the axial force on the plasma is greatly increased by the enhanced radial component of this field, and thereby aiding the rapid conversion of thermal to axial plasma velocity. It is worth noting that it also has the benefit of creating a strong magnetic barrier to any plasma-wall interaction.

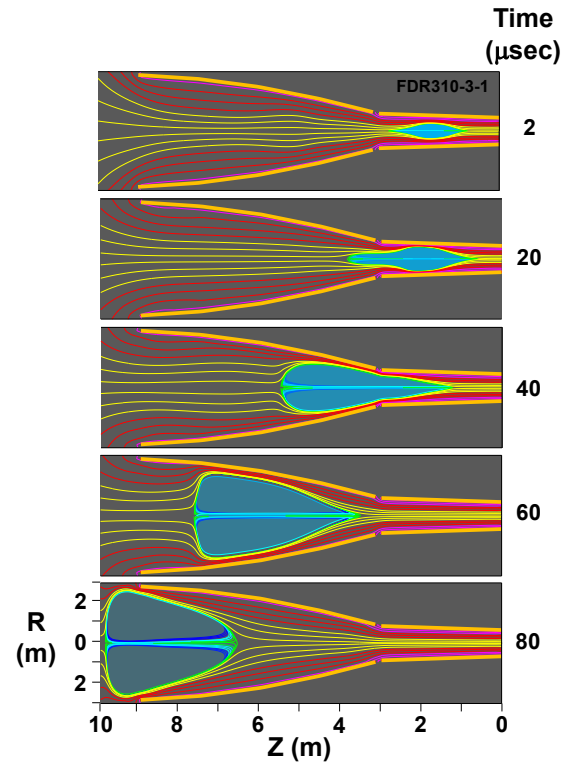


Figure 15. External flux lines and Li plasma regions from the 2D MHD calculation at various times during the of the post-fusion expansion, acceleration, and ejection from the Fusion Driven Rocket at scale.

The result of the MHD simulation of the post-fusion plasma temporal behavior can be found in Fig. 15 during this process. The calculation was simplified by assuming a constant spatial magnetic flux for both the nozzle and compression sections of the prototype FDR. After initialization of the fusion heated

Li plasma (aqua regions in Fig. 15), the flux is held constant in time for both coils so that no energy was added or removed from the system during the simulation. In this way the impact of the expanding post-fusion plasma on the spacecraft and thermal conversion processes could be more accurately determined. The rapid conversion of plasma thermal energy to directional energy is attested by the plots of the plasma thermal energy and plasma axial velocity as a function of time found in Fig. 16.

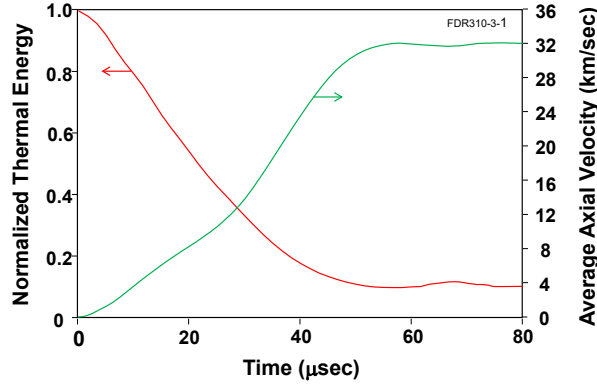


Figure 16. 2D MHD code results for the temporal evolution of the normalized plasma thermal energy (initial $E_{th} = 600$ MJ) and the plasma average axial velocity.

It can be seen that the conversion process starts before the plasma has expanded to the thruster wall. From Fig. 15 at roughly 40 μ sec the plasma's transverse motion has been halted and is in pressure balance with the compressed magnetic field. This represents the time when the external magnetic at the wall reaches its peak value of 3.5 T. While not a small field, it is well within the structural capability of many materials. The vacuum magnetic field needs to be no more than 10% of this field while still providing more than sufficient buffer distance at the wall during the plasma passage. The pressure that the thruster wall experiences is but a fraction of the plasma pressure achieved after fusion heating. This is due to the large volume expansion from centimeter to meter scale as well as conversion of the thermal energy to plasma directed motion. By the time of peak magnetic compression at the wall, the plasma thermal energy had been reduced to less than 20% of the peak thermal energy at initiation. Expansion down the nozzle continues to rapidly diminish the plasma energy density through expansion as well as converting thermal energy into directional flow albeit at a much-reduced rate due to the rapid drop-off in the radial component of the magnetic field at the wall.

The roughly 9% of unconverted thermal energy however does not have to be written off as a frozen flow loss. A large fraction can be recaptured into the energy storage system. This does require the nozzle to have a separate terminal section that is not just a passive conductor with a fixed magnetic flux as assumed in the modelling. It must have the ability for the wall current to flow into an auxiliary circuit.

The basic circuit diagram for the plasma thermal energy recovery can be found in Fig. 17. It is assumed that the solid-

state switch is conducting as the plasma passes into the "coil" so that the magnetic flux is kept constant with the magnetic field compressed inside the conductor. When the current is at the maximum, the switch is opened. This allows the plasma to expand and push the magnetic flux out of the nozzle inducing a voltage across the capacitor charging it. The capacitor charging occurs via the diode on a time scale of the

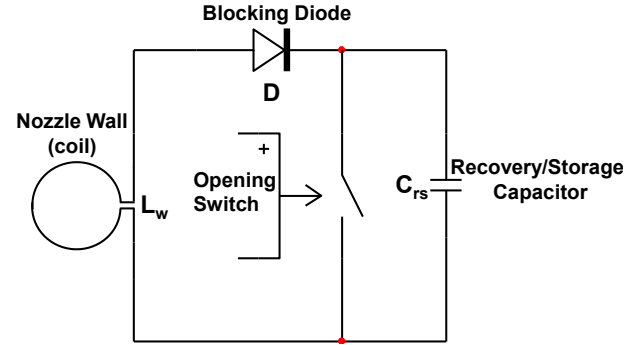


Figure 17. Simple circuit for energy recovery from Li plasma thermal energy at terminus of thruster nozzle.

plasma motion through the coil. On plasma exit the flux expulsion ceases and returns to the nozzle reversing the diode blocking any discharge from the capacitor. While such a scheme could recover as much as 80% of the remaining thermal energy, that is not necessary here. Since the remaining thermal energy represents 9% of the fusion energy released, it is roughly 300 times that of the energy delivered to the fusion plasma by the band driver circuits. Eighty percent of the remaining thermal energy would thus be over 20 times the input energy! Thus the recovery energy can be more than sufficient to power the plasma formation, band driver and all nozzle magnetic field coils for the next pulse.

Manned Mars mission analysis—The Copernicus orbit analysis software was used to determine that maximum Mars payload, assuming a limit of a 150 t initial launch to LEO and a 30 t return mass. Constrained by the ΔV budget of a 210-day round trip and a 50-day stay, it was found that a 50 t Mars lander was the maximum Mars payload. This mass was deemed reasonable considering a full Mars orbit insertion using the main FDR engine, which would minimize the thermal protection structural mass of the entry, descent, and landing systems.

The final mission architecture, therefore, consisted of a Trans-Mars Injection (TMI) maneuver with a ΔV of 7.6 km/s

Table 3. Mission Maneuvers

Maneuver	ΔV (km/s)	ΔT (days)	M_i (t)	M_f (t)	M_p (t)
TMI	7.6	4.5	225	180	45
MOI	13.8	6.0	180	120	60
TEI	16.2	2.6	68	42	26
EOI	11.8	1.2	42	30	12
TOTAL	49.4	14.3	---	---	143

over a 4.5-day period. Total propellant used during this maneuver was 45 t. The spacecraft would then coast 60 days before performing a Mars Orbit Insertion (MOI) burn to be captured into a Martian orbit. This burn would last a total of 6 days and use 60 t of propellant to achieve the ΔV of 13.8 km/s required. This would result in a total outbound trip time of 70.5 days. The 52 t Mars DAV with crew and supplies would descend to the surface and remain on the surface of Mars for 50 days. The DAV would then ascend and rendezvous with the FDR spacecraft delivering the crew, but remain in Marian orbit to be used by future missions. The spacecraft, including the Mars Transit-habitat and the Fusion Driven Rocket, would leave orbit to return to Earth. The initial mass of the returning spacecraft to Earth would be 68 t with a dry mass of 30 t. The Trans-Earth Insertion (TEI) maneuver to escape the gravity of Mars and set a trajectory back to Earth requires a ΔV of 16.2 km/s, requiring 26 t of

Table 4. Mission Maneuvers with PMS Braking

Maneuver	ΔV (km/s)	ΔT (days)	M_i (t)	M_f (t)	M_p (t)
TMI	7.6	2.5	125	100	25
MOI	0	---	100	100	0
TEI	16.2	1.8	48	30	18
EOI	0	---	30	30	0
TOTAL	23.8	4.3	---	---	43

propellant over 2.6 days. Again, the spacecraft coasts for 86 days before performing a final Earth orbit insertion maneuver to place the spacecraft back into its original circular 400 km orbit. These maneuvers require 11.9 km/s of ΔV and the remaining 12 t of propellant. With a burn time of 1.2 days, the total inbound transit time is 95 days, resulting in a total mission time of 210 days.

Table 3 summarizes the various parameters for the mission discussed. It can be seen that the lithium fuel requirement exceeds the one launch criteria of 150 t. The 225 t total mass to LEO, however, is still within the one-use range of the SpaceX starship of 250 t. It actually makes more sense to bring the fuel up as a separate launch which is under the 150 t limit. In fact, it is likely to proceed in this manner as it reduces risk and makes both launches considerably cheaper as the heavy lift is just fuel cargo. The separate fuel launch is what would occur in any case on future reuse of the FDR spacecraft.

It is worth calculating at this point as to how much Tritium is required for this mission. The total fusion energy for the mission can be obtained from the total burn time multiplied by the average jet power divided by the conversion efficiency, which yields $E_{fus}(total) = 9.1 \times 10^{13}$ J. The total number of fusion reactions required is $E_{fus}(total)/2.82 \times 10^{-12} = 3.2 \times 10^{25}$. The mass of the Tritons consumed is thus 0.16 kg. From the gain assumption the burn-up fraction is likely to be about 50% so that 0.32 kg of Tritium would be required to perform the mission.

Mission Variation for Faster Trip Times—Several variations of this mission architecture can be envisioned. A single launch to Mars was considered as it offered a design space that could not otherwise have been considered without the use of the unique capabilities of the Fusion Driven Rocket. As mentioned, a separate fuel launch would make more sense from a practical and safety point of view. Ignoring for the moment that one should not assume more than one miracle at a time, there is a method for significantly reducing trip time and increasing payload with no significant changes to the spacecraft operation as already outlined. It invokes a aerobraking technique that does not suffer from the mass penalty that was seen for solid shields. It is referred to as the Plasma MagnetoShell (PMS) [25]. The concept is based on achieving sufficient drag from ambient atmosphere, but at much higher altitude using a large-scale magnetized plasma “parachute” tethered to the spacecraft. Experiments at MSNW funded by NASA’s Innovative Advanced Concept (NIAC) program have demonstrated the feasibility of this

Table 5. Ultrafast Mission with PMS Braking

Maneuver	ΔV (km/s)	ΔT (days)	M_i (t)	M_f (t)	M_p (t)
TMI	17.3	6	150	90	60
coast		30			
MOI	(22.9)	~1	90	90	---
stay	---	22	90	60	---
TEI	23.6	3	60	30	30
coast		30			
EOI	(18.3)	~1	30	30	---
TOTAL	82.1	93	---	---	90

concept and outlined how it could be employed in space for just the kind of rapid, high ΔV braking required for MOI and EOI. Given the many unknowns and substantial challenges to successfully develop the Fusion Driven Rocket, the Plasma MagnetoShell looks to be a “gimmie” in comparison.

Based on the initial analysis of the PMS requirements for aerobraking, it will be assumed in the mission analysis that MOI and EOI will be performed by the essentially massless PMS system in less than day. Reanalyzing the 210-day mission, one can find the new summary of ΔV maneuvers for this mission in Table 4. The total mass for the mission is now 125 t, needing only 43 t of Lithium propellant. This would allow for either more payload or a shorter trip time. It would clearly be payload for the 210-day trip. The question was explored as to how short a trip time would be feasible employing the PMS for braking without sacrificing too much time at Mars.

For this type of mission, if predeployed assets are to be avoided or minimized, both the payload (DAV) for Mars and the Trans-habitat (MTV) would need to be reduced. The payload for Mars could be reduced from 50 t to 30 t. This should provide enough mass for both habitat and fuel for a smaller crew to land and return the spacecraft. It would still

be twice the mass of the Eagle lunar lander. If a more elaborate DAV is desired, it could be predeployed in Martian orbit awaiting the arrival of the FDR spacecraft two years hence. The stay time would also be reduced from 50 days to

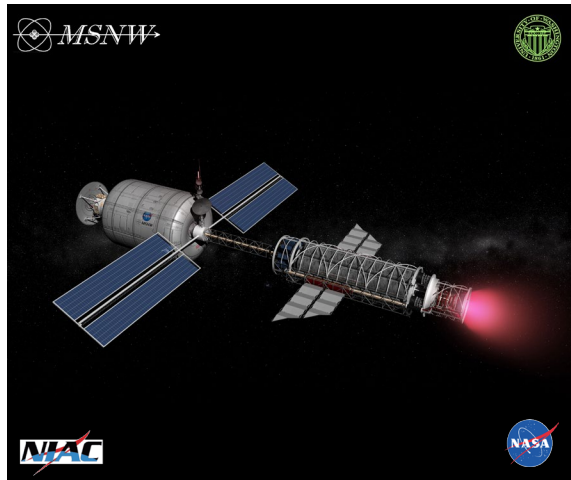


Figure 18. Artist rendition of the Fusion Driven Rocket.

22 days. This class of mission could be thought of as a precursor or exploratory type mission, so that less time and equipment would be needed at the surface. It could also be used to resupply or replace crew when a more permanent manned presence is established on Mars much like the space shuttle had provided for the ISS. The mission details for this ultrafast trip are found in Table 5. Despite the very large ΔV s required, the IMLEO mass is within the 150 t target for a single launch.

A notion as to what the Fusion Driven Rocket for a manned Mars mission would look like is found in Fig.18. Included in the rendering are the requisite fuel storage, pulse power system, shock absorbers, radiation shields, heat radiators, solar panels, and last but not least, the crew habitat based on DRA5.

6. CONCLUSION AND FUTURE WORK

Most of the experimental work reported here was accomplished during a NIAC phase I and II research grant on the Fusion Driven Rocket. The results elevated the concept Technology Readiness Level (TRL) from somewhere around

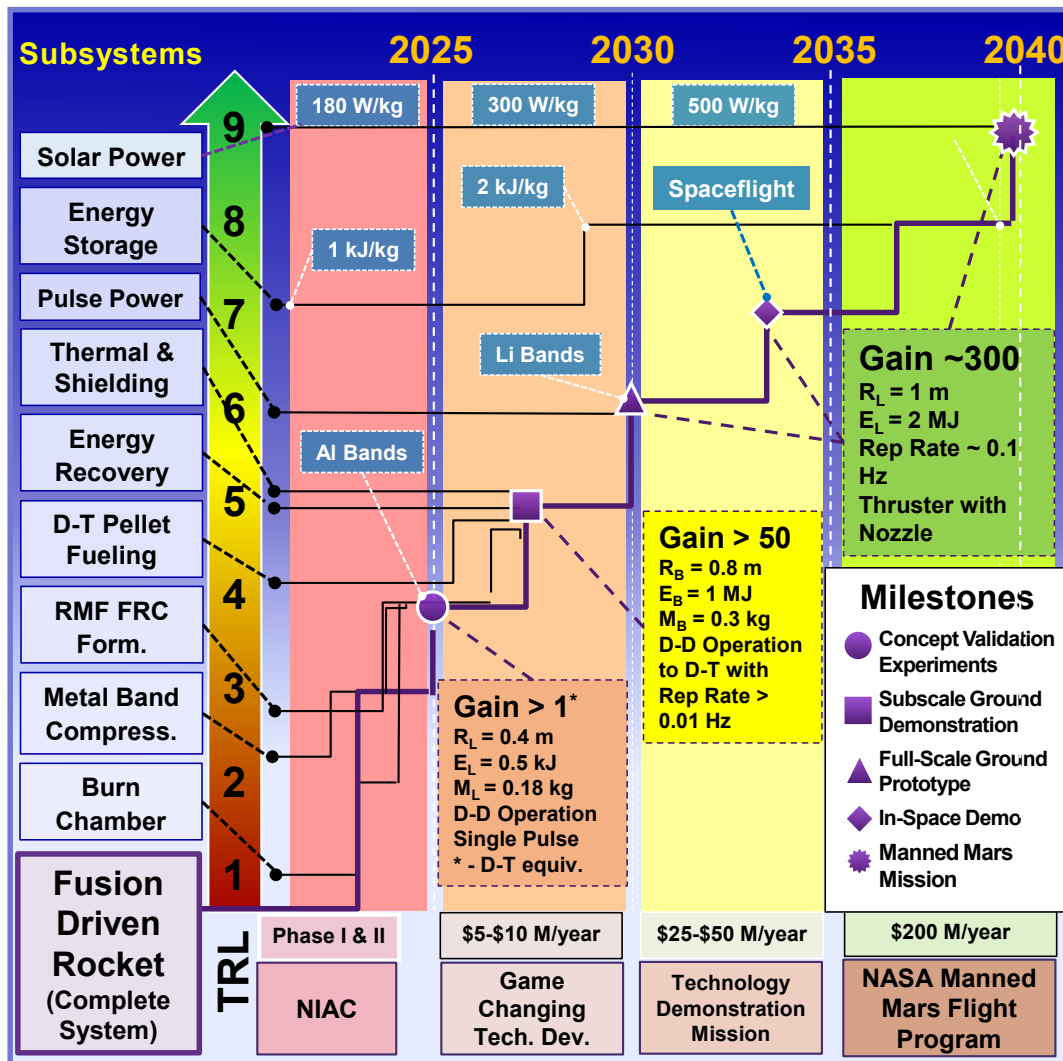


Figure 19. Technology Roadmap for the Fusion Driven Rocket.

TRL 1 to TRL 3. At the end of that study, it was concluded that the next step for future development of the FDR would be the metal band compression of the FRC to fusion conditions and thereby bring the TRL to 4. There was not sufficient funding or time to attack this key task, but it was, and still is, the hope that this experimental goal can be achieved in the future with further funding. This would be a major step in demonstrating both the fusion physics and technology, and would validate the FDR concept as a feasible approach.

Since the NIAC work, an improved understanding of the physics involved, as well as the advantages of employing the RMF formed FRC, led to an updated analysis of the design and operational scheme for the FDR as presented here. The prospects for success have been substantially improved, making the performance of the validation experiments even more imperative. Of course, success in this experimental endeavor would not be sufficient to claim the same status for the full complement of subsystems required to make it a viable rocket. While most components required for the full FDR system are already at a higher stage of technological development, their suitability to meet the challenges required for the FDR needs to be experimentally confirmed as well. A roadmap for the full development of the Fusion Driven Rocket has been outlined for all the major subsystems required, and are listed in Fig. 19. Their initial TRL level is given with regard to application on the FDR, along with a timeline for evolving all of the subsystems the FDR to reach TRL 9. The figure also lists key milestones to be achieved in order to achieve the goal of a manned mission to Mars in the early 2040s. Also included is a guesstimate of the yearly costs to reach the several milestones.

Needless to say, there will also be a need for a significant upgrade in the theoretical analysis tools in order to ensure that the experimental tests are carried out in the most propitious manner possible. This will not be a trivial task as one will most likely need a 3D code that can elucidate the physical behavior of the Lithium bands through all four states of matter, i.e. solid, liquid, gas, and plasma. It must also do this in a manner that can be coupled to an MHD package that can also incorporate the significant thermal effects from the nuclear fusion products. However, if these endeavors are successful, the result will be a practical and efficient nuclear fusion based propulsion system for manned exploration of the solar system.

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BIOGRAPHY



John Slough received his B.A and PhD in Astrophysics from Columbia University. He has spent over 30 years working in the field of experimental physics. He founded MSNW in 1991, a small business with a long history in the research and development of advanced space propulsion and plasma physics technologies. He was the principal investigator on several large fusion-related projects funded by the Dept. of Energy. Experiments performed by Dr. Slough led to advances in the formation and confinement of FRCs as a fusion concept as well as a better understanding of the relevant physics. Recently, he founded a spin-off company, Helion Energy, to develop a commercial fusion reactor which has received both DOE and venture capital funding. Dr. Slough was also on the faculty in the Astronautics and Aeronautics Dept. at the University of Washington for many years.