

The Fusion Driven Rocket

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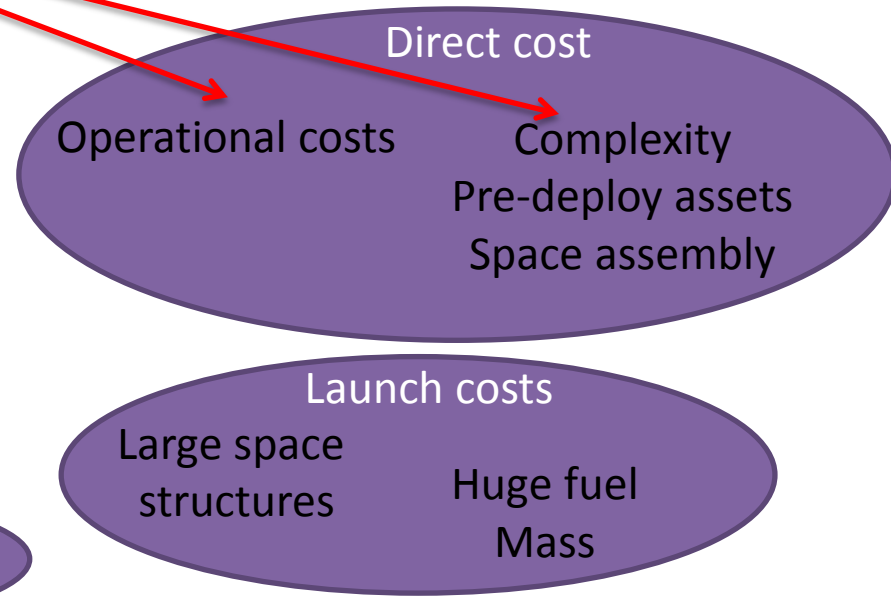
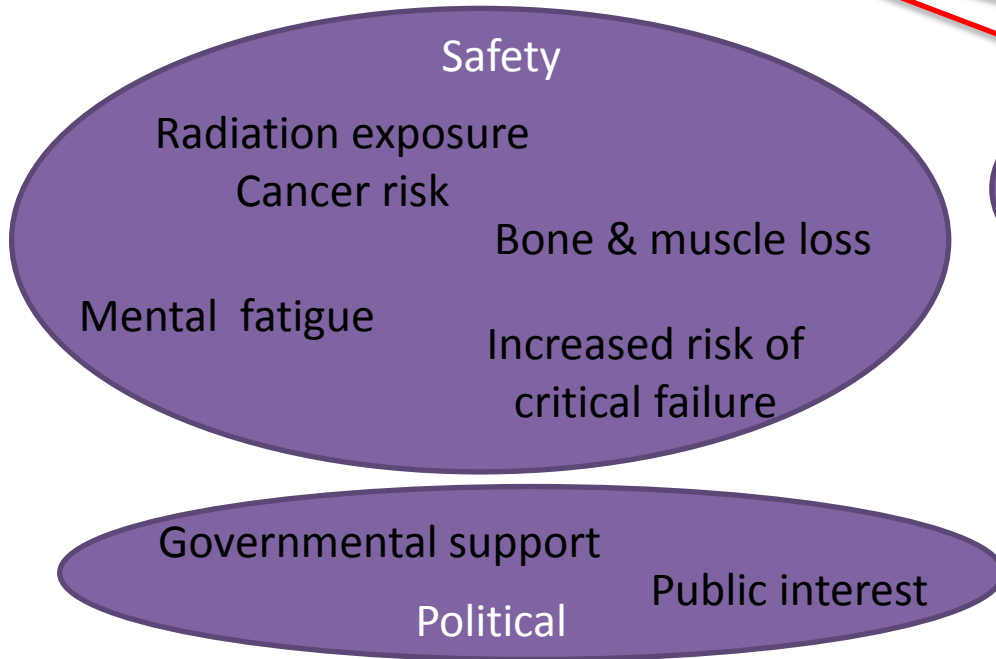
Hampton, VA, November 2012

- **Background**
- **Benchmarks of FDR program**
 - Mission Architecture Study
 - Spacecraft Design
 - Theoretical work
- **Research Plan**
 - Experiment validation
 - Numerical & Analytical Studies
 - Spacecraft Design
 - Mission Architecture
- **Roadmap**

Why We Are Not on Mars Yet?

Takes too long

Costs too much



Solution: New method of propulsion is needed

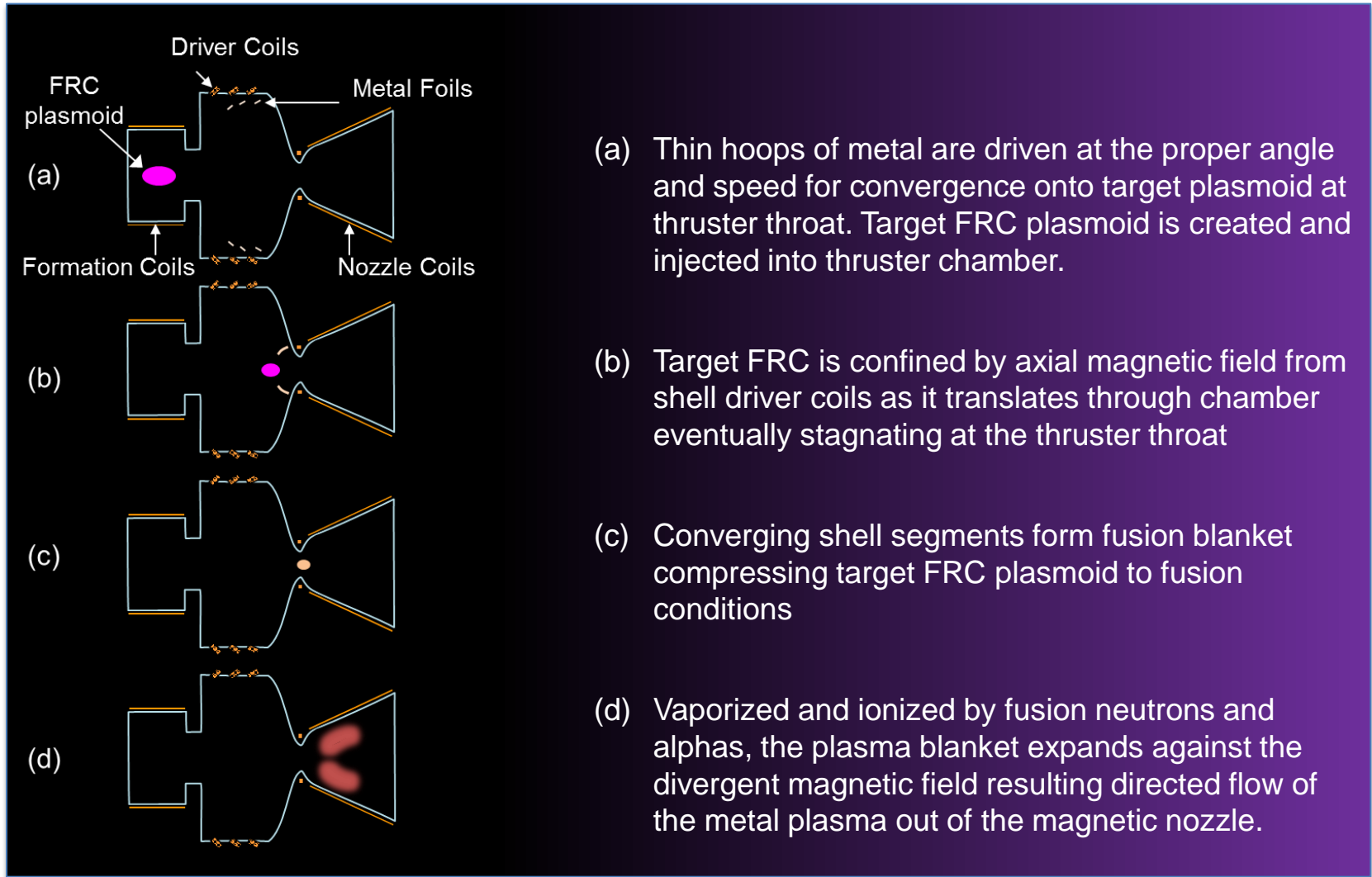
Short trip time

Reduced IMLEO

High $\frac{\text{Engine Power}}{\text{Spacecraft Mass}} (\alpha)$

High Exit Velocity (I_{sp})

The Fusion Driven Rocket



Schematic of the inductively driven metal propellant compression of an FRC plasmoid for propulsion

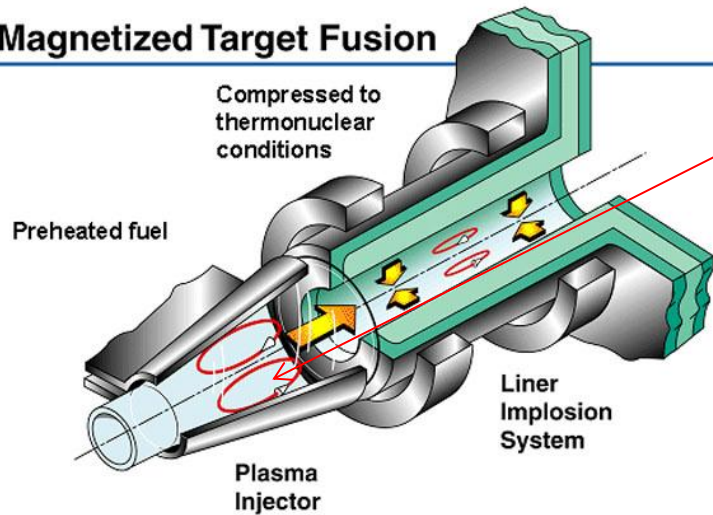
Magneto-Inertial Fusion

Two Approaches

Shell (liner) implosion driven by B_θ from large axial currents in shell.

Liner implosion from $j \times B$ force between external coil and induced liner currents

Magnetized Target Fusion

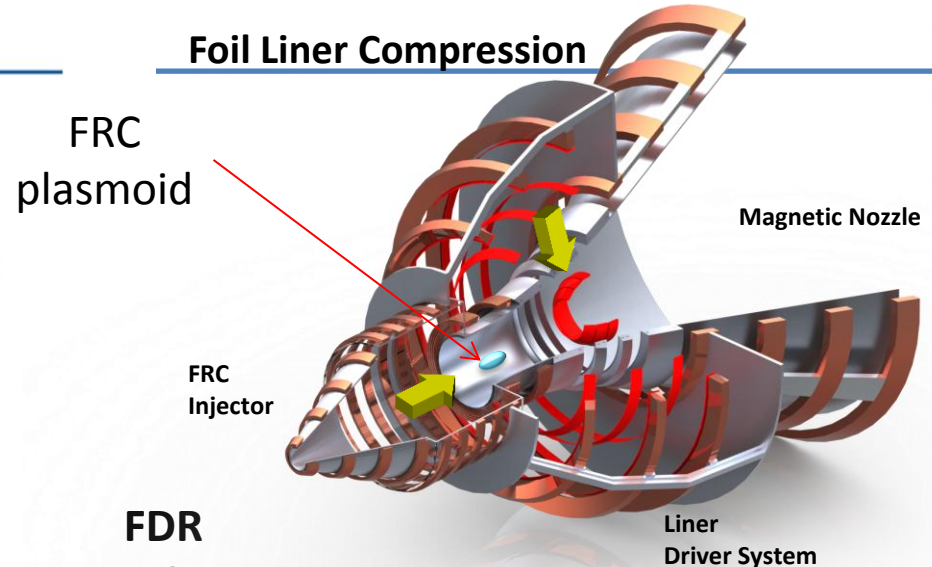


MTF

Issues:

- Extremely low inductance load difficult to drive (massively parallel HV caps and switches)
- Close proximity and electrical contact \Rightarrow major collateral damage with each pulse
- Small FRC must be formed close to implosion \Rightarrow marginal B for ignition w injector destruction
- Only inefficient 2D compression possible \Rightarrow requires much larger driver energy

Foil Liner Compression



FDR

Advantages:

- Large driver coil easy to power with ample standoff
- Driver electrically isolated from liner and magnetically from fusion process
- Large FRC can be formed external to implosion with abundant B for ignition
- Full 3D compression can be realized for efficient compression and translation

FDR offers the first realistic approach to fusion-based propulsion

	Benefit	Result
1	Direct transfer of fusion energy to the propellant	High efficiency, low mass engine
2	Uses solid propellant	No significant tankage
3	High exhaust velocities (2000- 5000s Isp)	Short trip time, high mass fraction Low IMLEO
4	Magnetic insulated reaction chamber and nozzle	No significant physical interaction with the spacecraft Minimal thermal heat load and Low radiator mass
5	Low energy requirements to achieve MIF	Low mass (single launch) and greatly reduced cost

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Initial Mission Studies

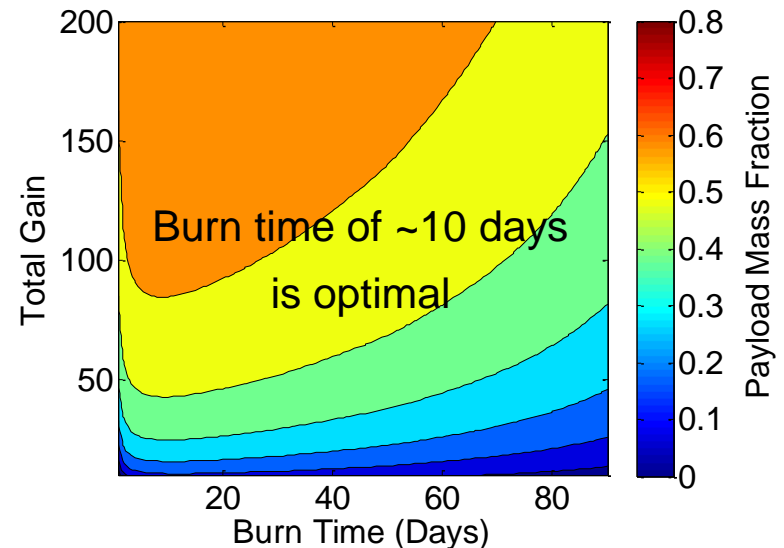
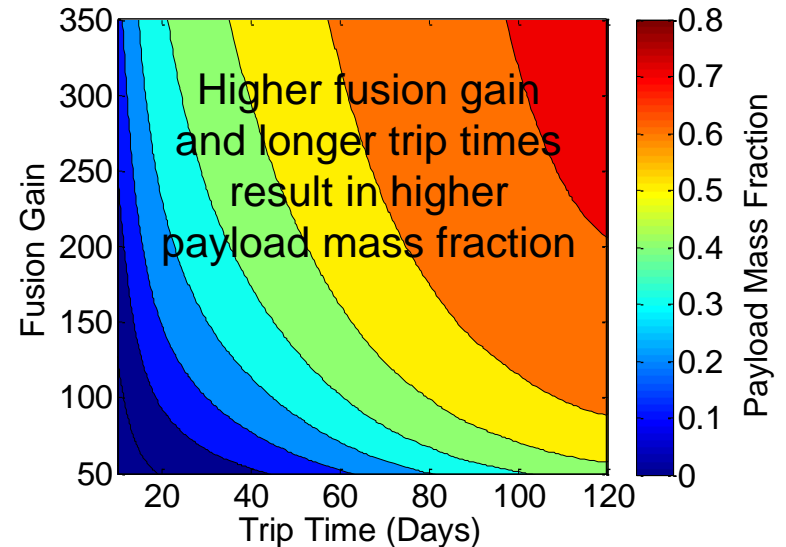


Fusion Assumptions:

- Ionization cost is 75 MJ/kg
- Coupling Efficiency to liner is 50%
- Thrust conversion $\eta_t \sim 90\%$
- Realistic liner mass are 0.28 kg to 0.41 kg
 - Corresponds to a Gain of 50 to 500
- Ignition Factor of 5
- Safety margin of 2: $G_F = G_F(\text{calc.})/2$

Mission Assumptions:

- Mass of Payload= 61 MT
 - Habitat 31 MT
 - Aeroshell 16 MT
 - Descent System 14 MT
- Specific Mass of capacitors $\sim 1 \text{ J/g}$
- Specific Mass of Solar Electric Panels 200 W/kg
- Tankage fraction of 10% (tanks, structure, radiator, etc.)
- Payload mass fraction = Payload Mass/Initial Mass
- System Specific Mass = Dry Mass/SEP (kg/kW)
- Analysis for single transit optimal transit to Mars
- Full propulsive braking for Mars Capture - no aerobraking



Fusion Equation

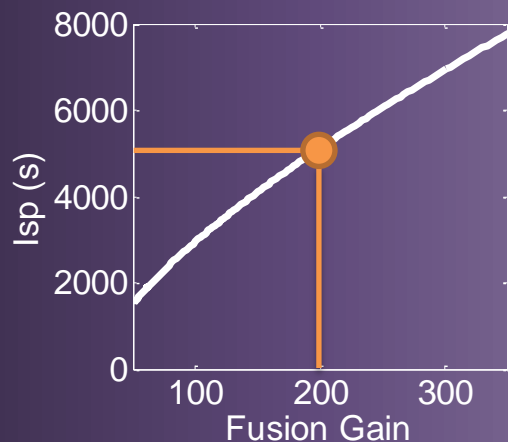
$$E_{out} = G_F E_{in}$$

$$G_F = 1.1 \times 10^{-7} M_L^{1/2} E_L^{11/8}$$

$$E_{in} = E_L = \frac{1}{2} M_L v_L^2$$

$$E_k = \eta_T (E_{out} - \Psi_{ion} M_L)$$

$$I_{sp} = \frac{(2E_k / M_L)^{1/2}}{g_0}$$



Isp = 5000 s

Power Input = 180 kW

Gain 200

Power(Jet) = 36 MW

Spacecraft Mass = 15 MT

Payload Mass = 61 MT

210 day Round-trip Manned Mars Mission

30 days

61 MT payload

83 MT

27 MT

97.1 days

134 MT

15 MT

FDR

1 launch

134 MT

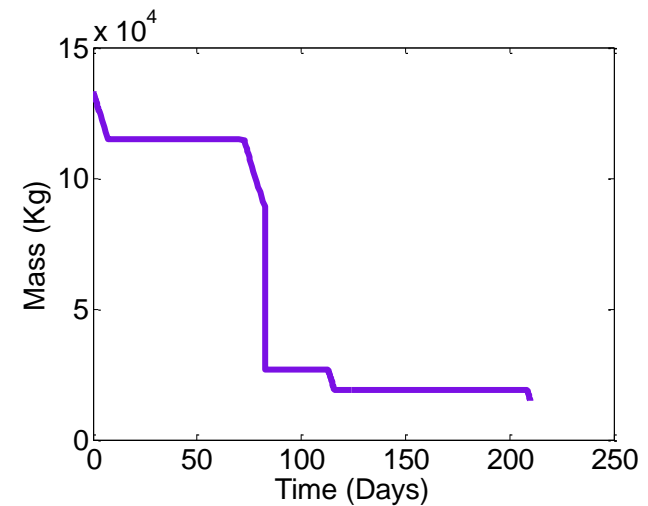
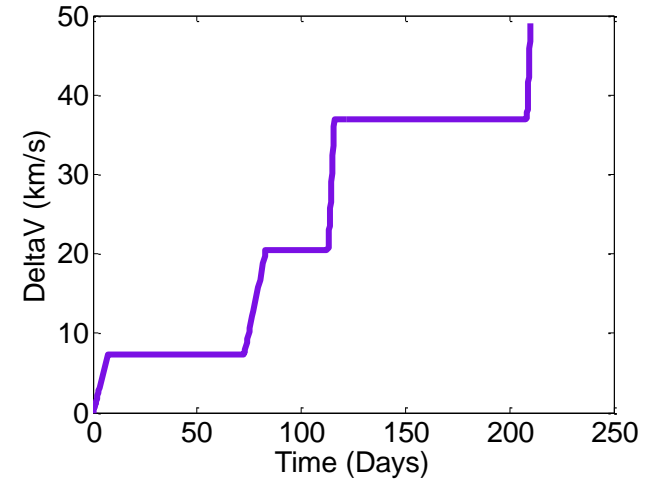
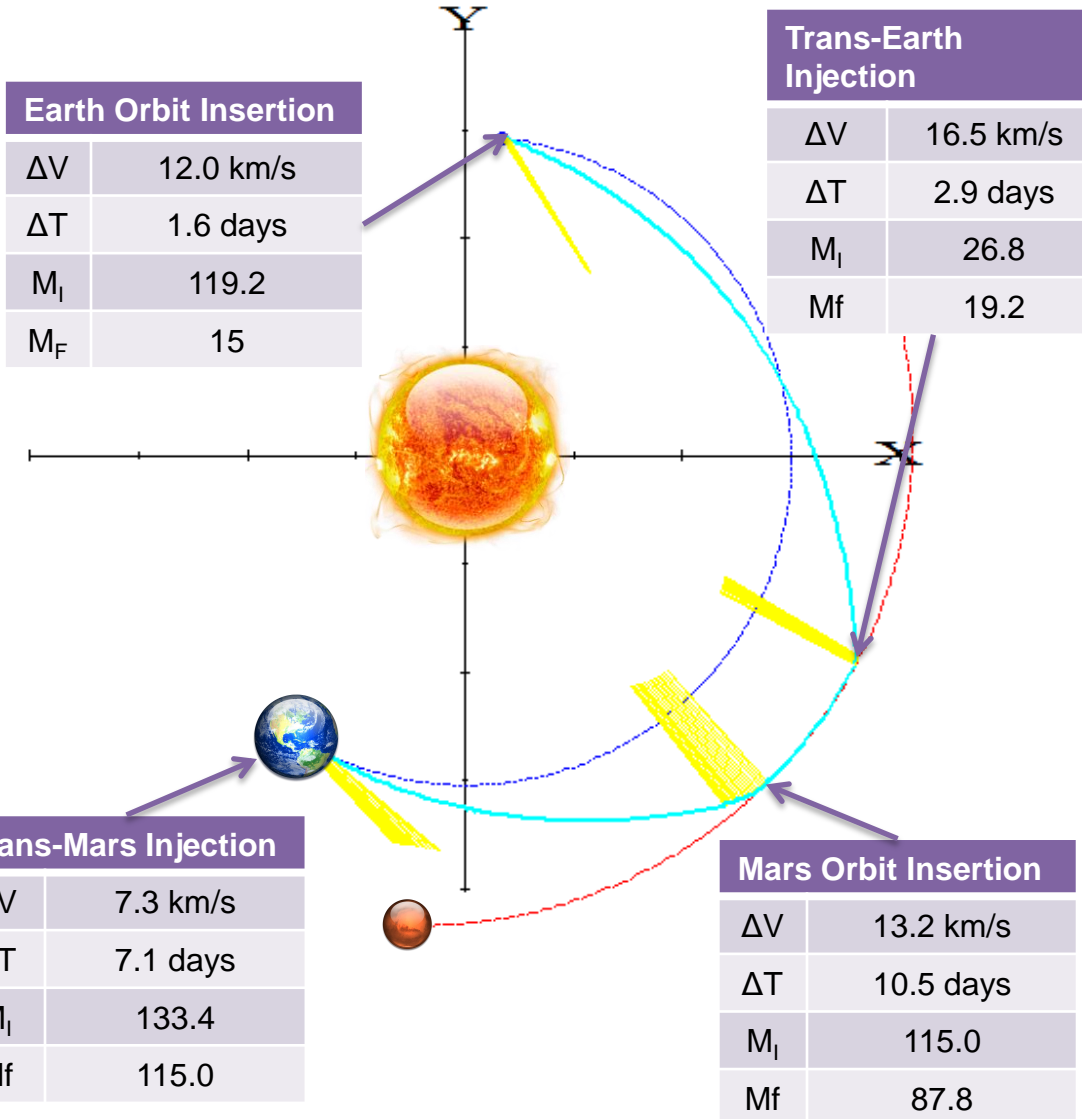
(IMLEO)

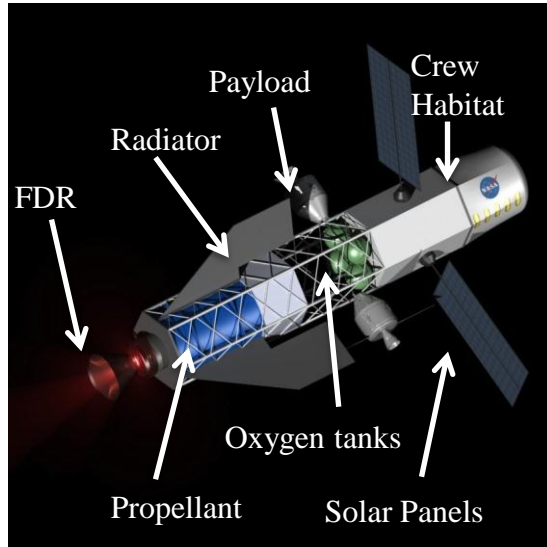
210 days

Refuel
Re-crew
For future
missions

DRA 5.0 (NTP), 9 launches, 848.7 MT IMLEO, 1680 days

210 day Round-trip (Mission Details)





Artists rendition of the FDR spacecraft

Spacecraft Component	Mass (MT)
Spacecraft structure ¹	6.6
Lithium containment vessel	0.1
FRC Formation ²	0.2
Propellant Feed mechanism	1.2
Energy storage ³	1.8
Liner driver coils ⁴	0.3
Switches and cables ⁵	1.8
Solar Panels ⁶	1.5
Thermal Management	1.3
Magnetic Nozzle	0.2
Spacecraft Mass	15
Crew habitat (DRA5.0)	61
Lithium Propellant	57
Total Mass	133

Payload mass fraction 46%

1. Fairings, support structure, communication, data handling ACS, Batteries
2. Hardware responsible for formation and injection of Fusion material (FRC)
3. Capacitors (1.8 MJ @ 1 kJ/KG), switches, power bus
4. Electromagnetic coil used to drive inductive liner
5. Pulsed power electronic components need to charge and discharge capacitor bank
6. 180 kW @ 200 W/kg

Circuit Parameters

$R=3 \text{ m}\Omega$
 $L=20 \text{ nH}$
 420 uF
 $40,000 \text{ V}$

Source Free RLC Circuit

$$V = L \frac{dI}{dt} + I \frac{dL}{dt} + IR$$

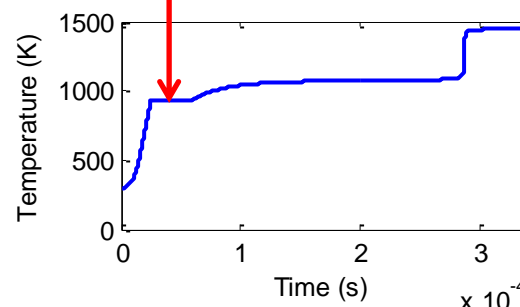
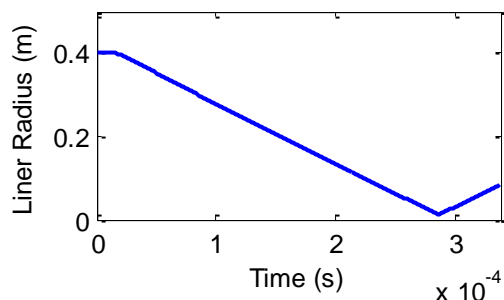
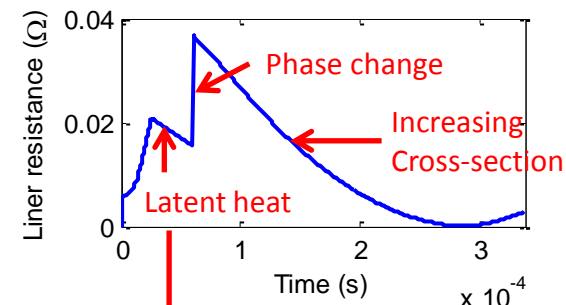
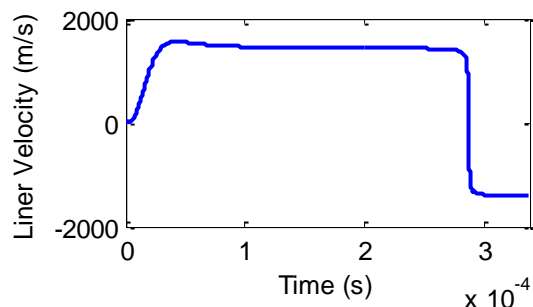
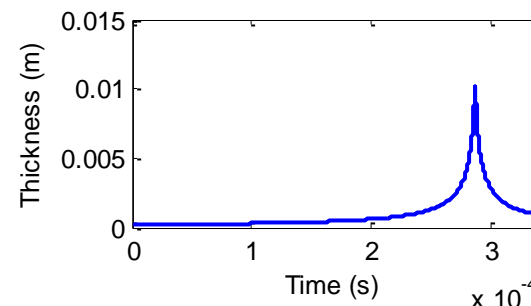
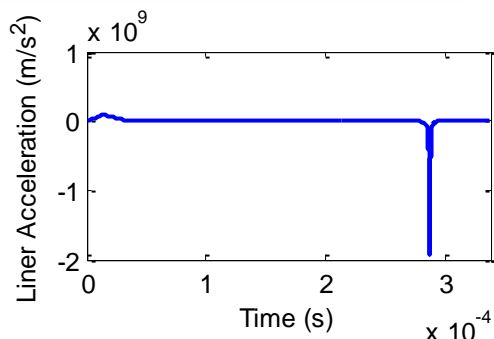
$$I = C \frac{dV}{dt}$$

changing inductance

Solved as 2 First Order equations

Liner Parameters

$r=0.41 \text{ m}$
 $w=6 \text{ cm}$
 $l=0.2 \text{ mm}$



- Various Current waveforms
 - Ringing
 - Crowbar
 - Diode
- Magnetic flux diffusion
- Resistivity - $\rho(T)$
- Latent heats
- Radiative cooling
- Energy conservation

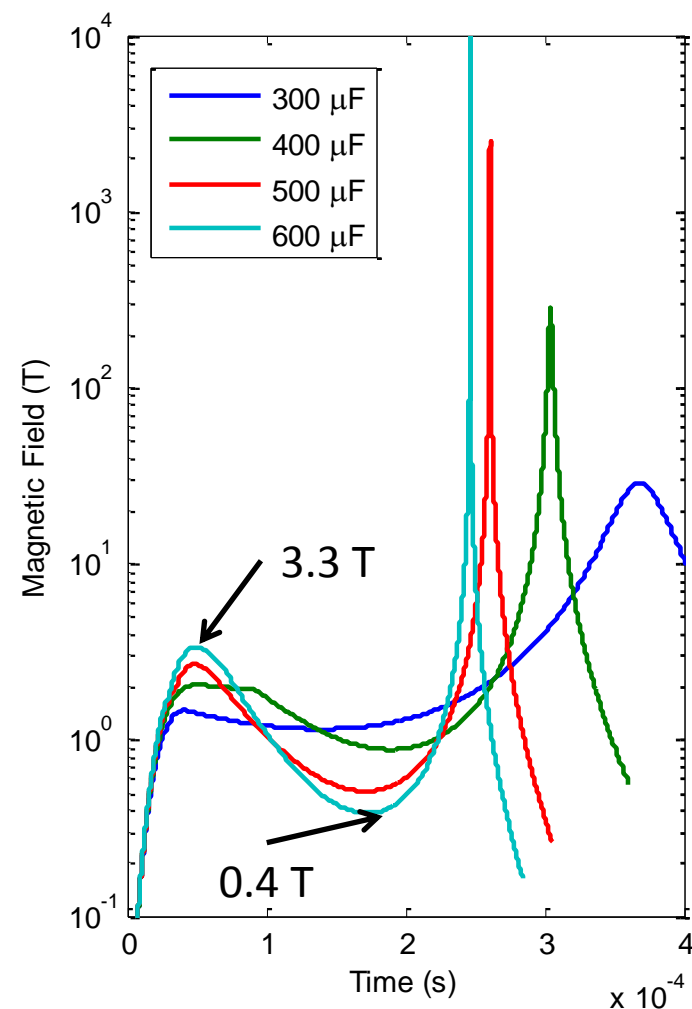
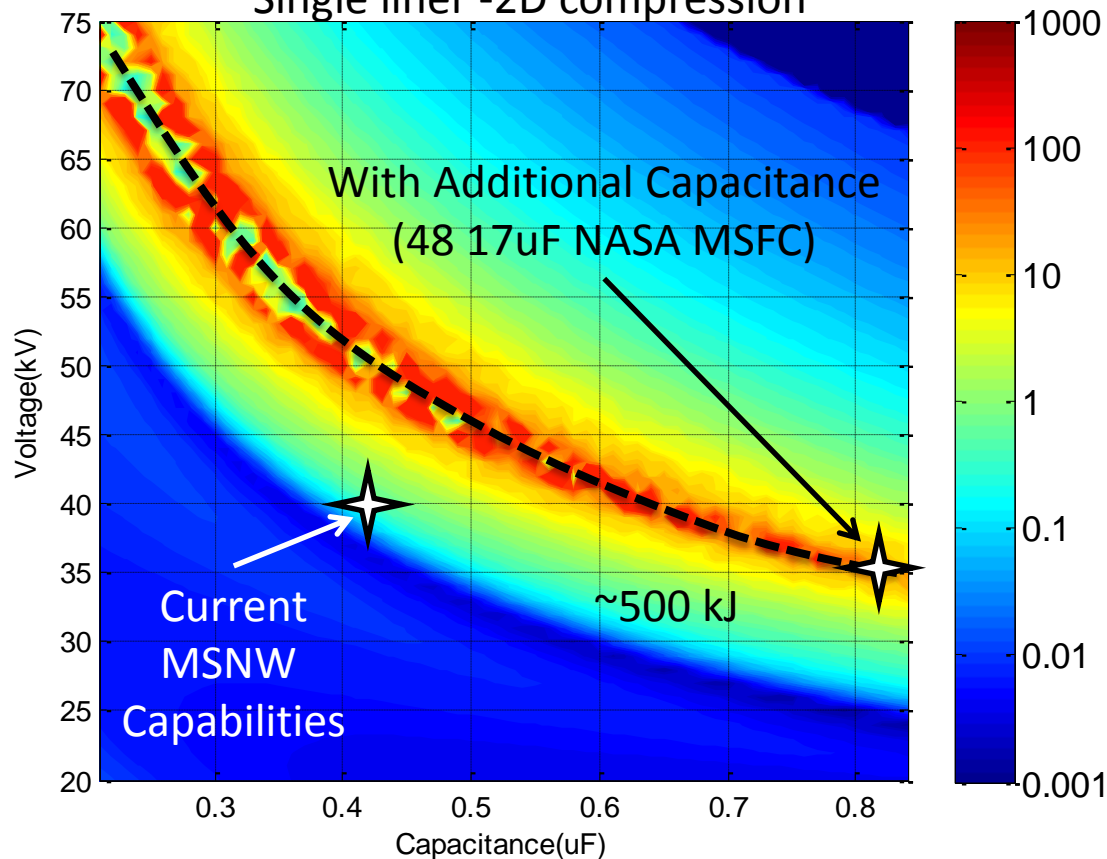
Data for actual coil and
 collector plate used
 In Foil Liner Compression
 (FLC) Test bed

Possible operating condition

$$Yield = E_{fus} / E_{input} \cong \frac{1.2 \times 10^{-12}}{(2\mu_0 e)^2} B_0^4 r_l^2 l_l \tau_D / E_{input}$$

Dwell time (70% of peak field)

Single liner -2D compression



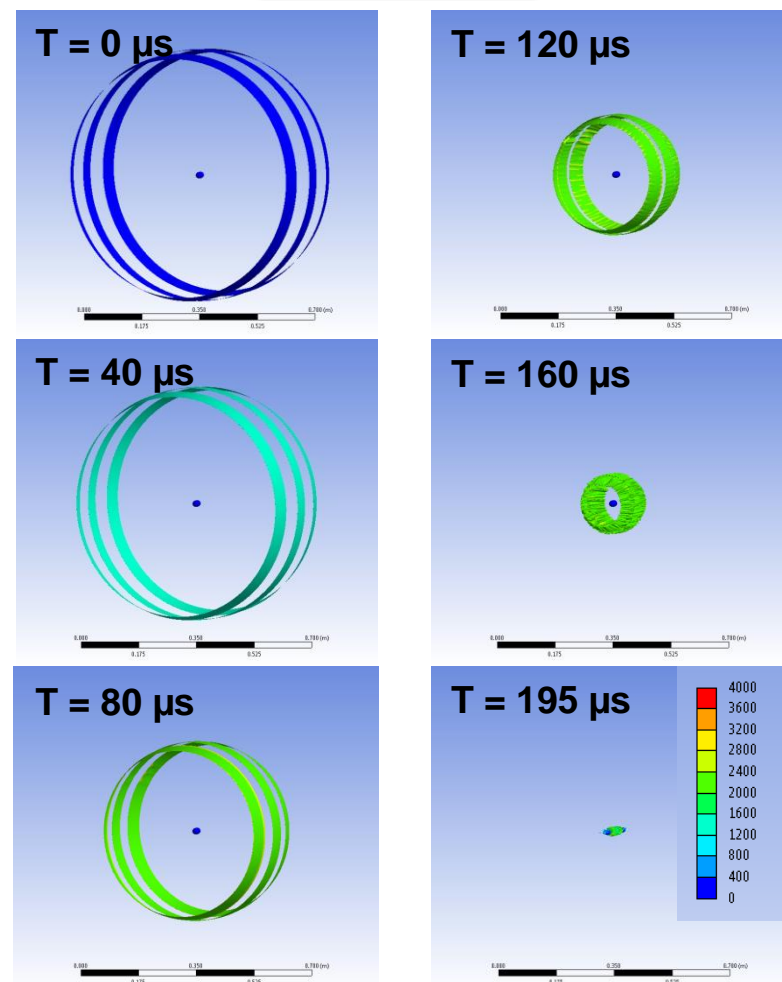
$$B_{in}^n = B_{in}^{n-1} \left(\frac{r^{n-1}}{r^n} \right)^2 + \Delta B^n$$

$$\Delta B^n = (B^n - B_{in}^{n-1}) \left(\frac{L_L}{R_L} \right)^{-1} dt$$

ANSYS Explicit Dynamics[®] Calculations



- Three 0.4 m radius, 5 cm wide, 0.2 mm thick Aluminum liners converging onto a stationary test target.
- First 3D structure compression of metallic liner
- No gross instabilities were observed due to the structure rigidity of the material
- Forces are well beyond the plastic deformation limit of the material, resulting in a uniform compression
- Low internal energy from the liner compression which is different from plasma or thick liner compression



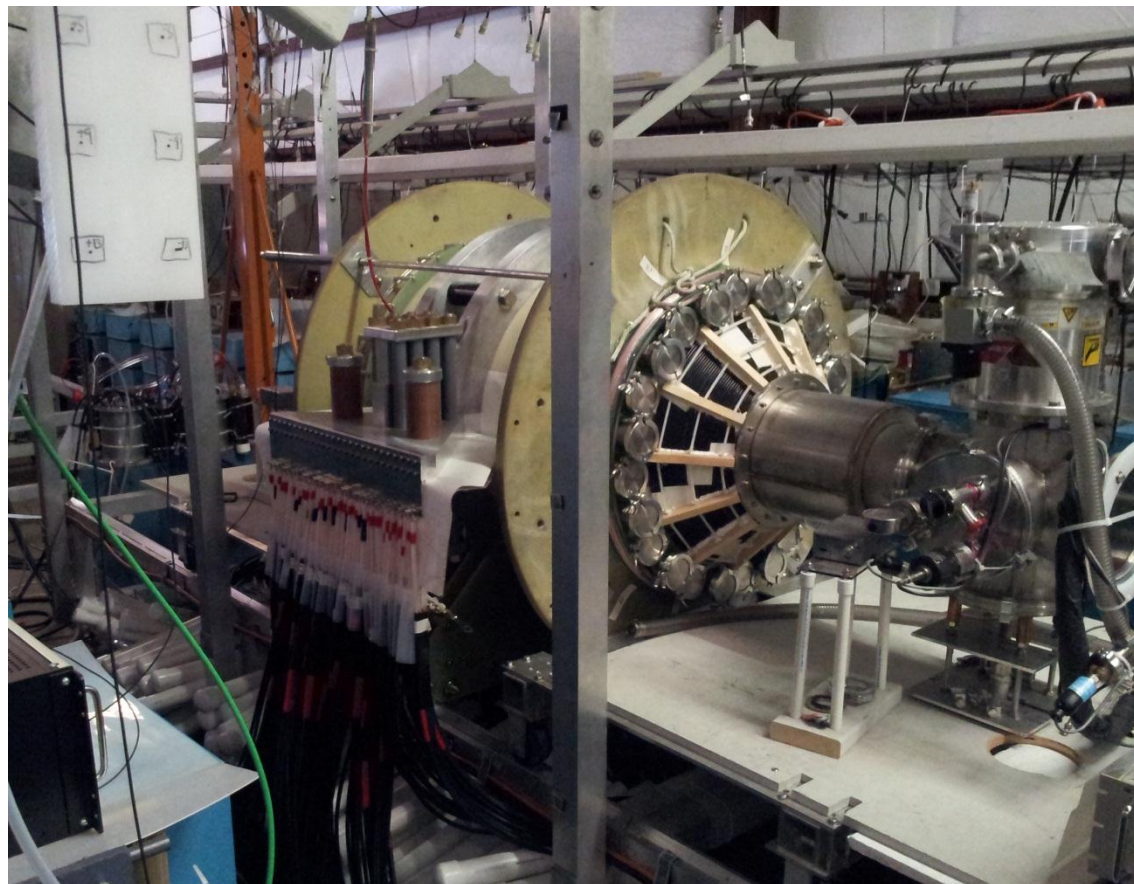
Liner behavior agreed very well with 1D Liner Code

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- Roadmap

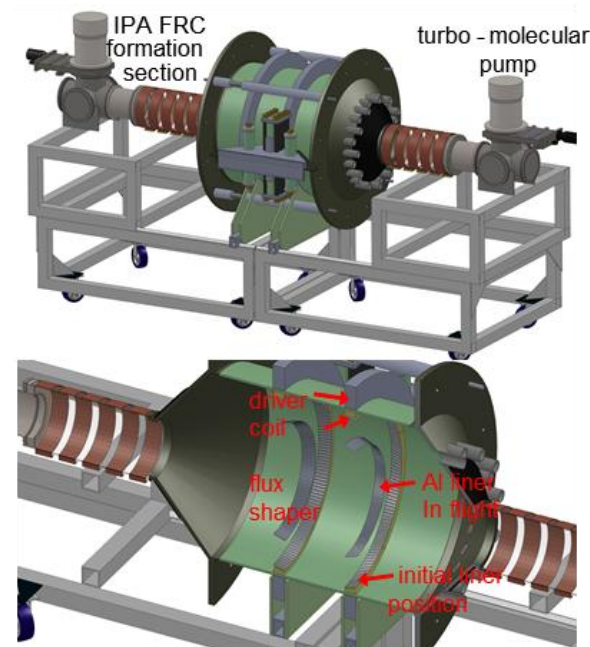
Research Plan

Task 1 – Fusion Physics – Experimental

IDL Unity Gain Validation Experiment at MSNW



Picture of the FDR validation experiment construction now underway.



CAD rendering of the Foil Liner Compression (FLC) test facility at MSNW

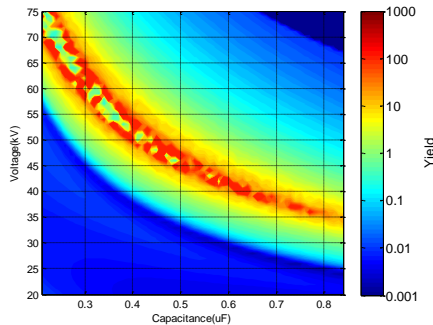
Milestones

- Pulse Power System operation at rated voltage (6 mo)
- Double liner compression demonstrated (1 yr)
- Megagauss (100T) field compression achieved (1.5 yrs)
- FRC operation (2 yrs)

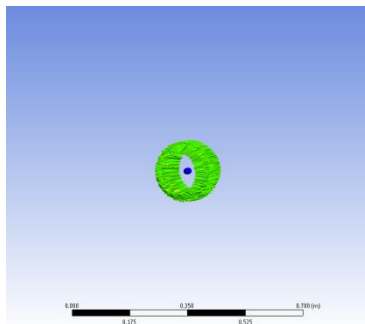
Research Plan

Task 2 – Numerical & Analytical Studies

1D Liner Compression Model



3D ANSYS Simulation



➤ Liner dynamics trade studies

- Liner energy
- Magnetic pulse shaping
- Bias field
- Geometry
- Scale
- Mass
- Temperature

➤ Analysis of lithium propellant

➤ Full scale FDR engine analysis

- Thermal analysis
- Structural analysis

➤ Apply model results to refine:

- Spacecraft design
- Mission architecture

➤ Model fusion neutronics

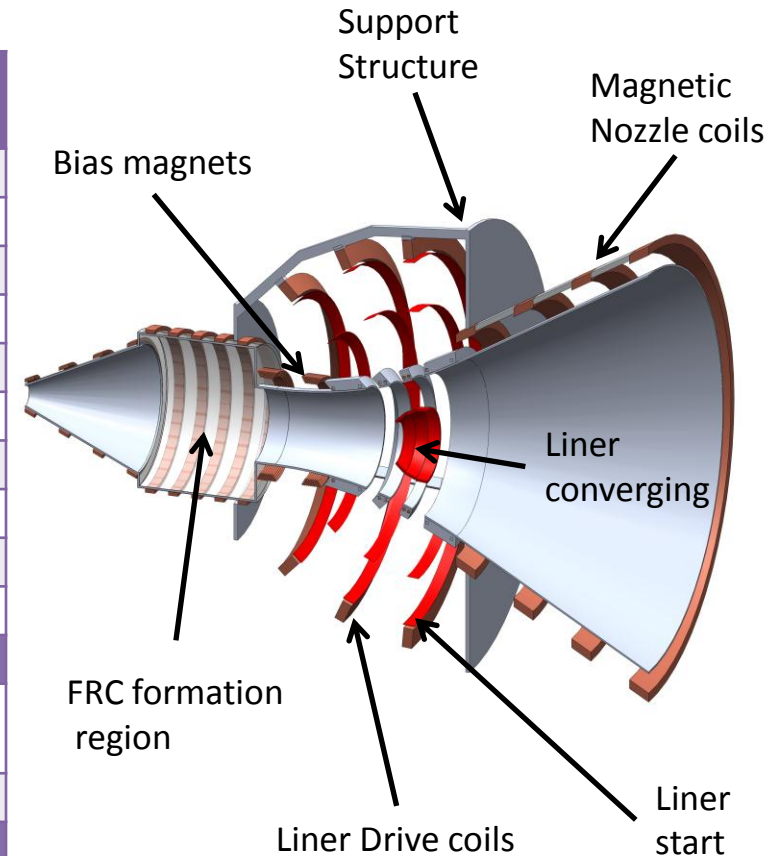
Milestones

- 2 coil 1D compression model (6 mo)
- FDR engine design (1 yr)
- 3D Thermal analysis (1.5 yr)
- Fusion/spacecraft interaction characterized (2 yr)

Research Plan

Task 3 – Spacecraft Design

Spacecraft Component	Mass (MT)	TRL	Mission Dependent	Fusion Dependent
Spacecraft structure	6.6	4	X	
Propellant tank	0.1	5	X	X
FRC Formation	0.2	4		X
Propellant Feed	1.2	2		X
Energy storage	1.8	7		X
Liner driver coils	0.3	3		X
Switches and cables	1.8	6		X
Solar Panels	2.7	8	X	X
Thermal Management	1.3	5		X
Nozzle	0.5	2		X
Spacecraft Mass	15		X	X
Crew habitat	61		X	
Propellant	57		X	X
Total Mass	133		X	X



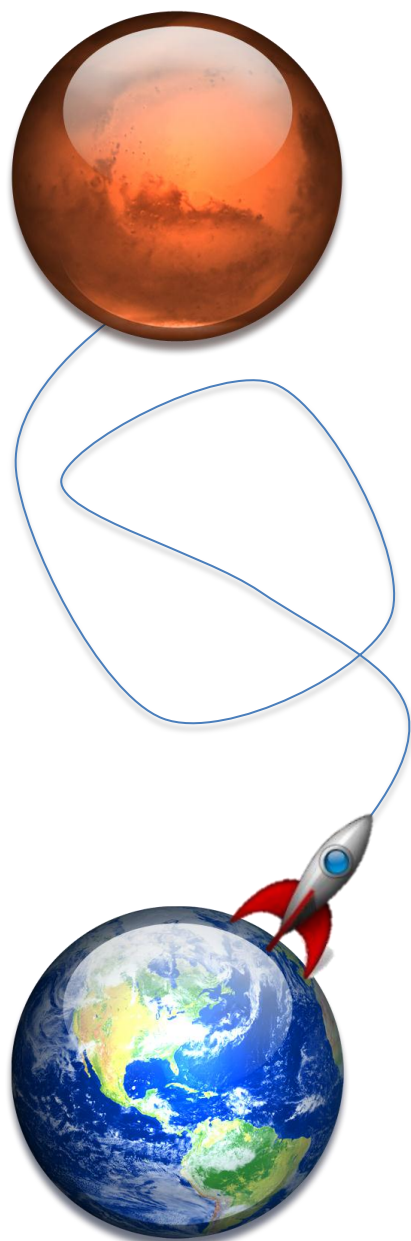
Milestones

- Initial TRL assessment (6 mo)
- FDR flight system design (1 yr)
- Detailed Hardware list (1.5 yrs)
- Overall spacecraft design (2 yrs)

**For a more accurate spacecraft design and total launch mass
A more defined mission and fusion conditions are need**

Research Plan

Task 4 – Mission Architecture



➤ Mars

- Single launch to Mars (Sortie)
 - Mission refinement
- Long Stay Mission (>500 day)
- Single trip – on orbit assembly
 - Larger s/c (fuel launched separate)
- Pre-deploy mission architecture
 - Classic DRA style with pre-cursor cargo mission
- Ultra-fast (30 day) transfers

➤ Jupiter

- Enter and exit gravity well
- Moon mission

➤ NEO

- Sample return
- Redirection?

Milestones

- Investigate relevant Mars missions (6 mo)
- Incorporate 1D Compression code results (1 yr)
- NASA assisted high fidelity mission design (1.5 yr)
- DRA report based on FDR (2 yrs)

Research Plan

Technology Roadmap for the Fusion Driven Rocket

