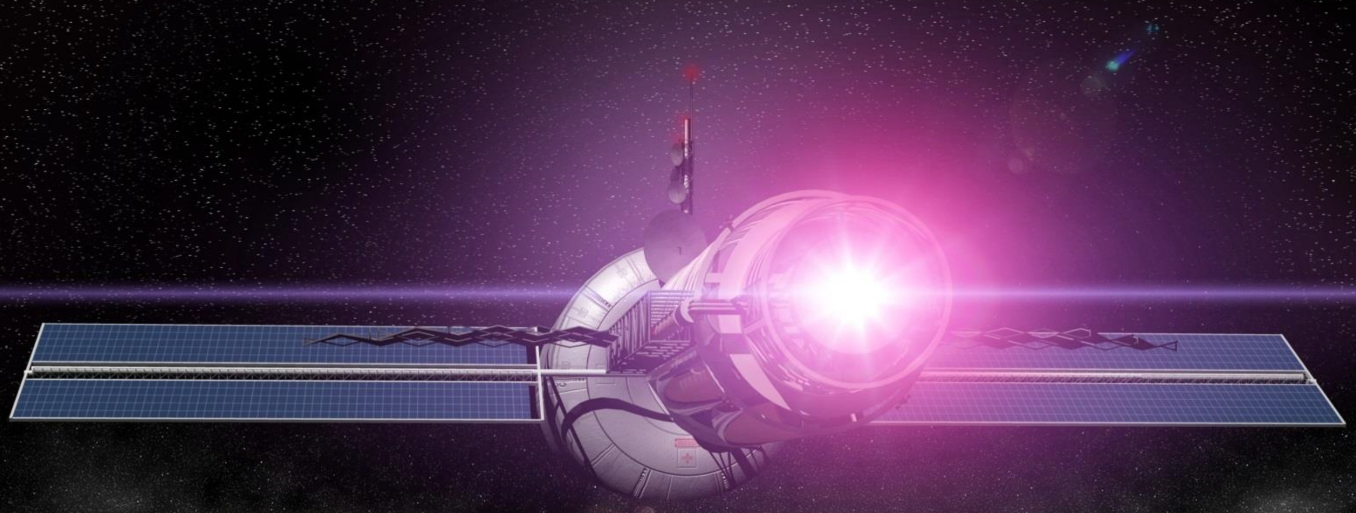
The Fusion-Driven Rocket



Anthony Pancotti
John Slough, David Kirtley, George Votroubek, Christopher Pihl

MSNW LLC, Redmond, WA, 98052

1. **Background**
2. Mission Architecture Design
3. Spacecraft Design
4. Fusion Physics

Why We Are Not on Mars Yet?

Takes too long — **Costs too much**

Safety
- Radiation exposure
- Cancer risk
- Bone & muscle loss
- Mental fatigue
- Increased risk of critical failure

Direct cost
- Operational costs
- Complexity
- Pre-deploy assets
- Space assembly

Launch costs
- Large space structures
- Huge fuel Mass

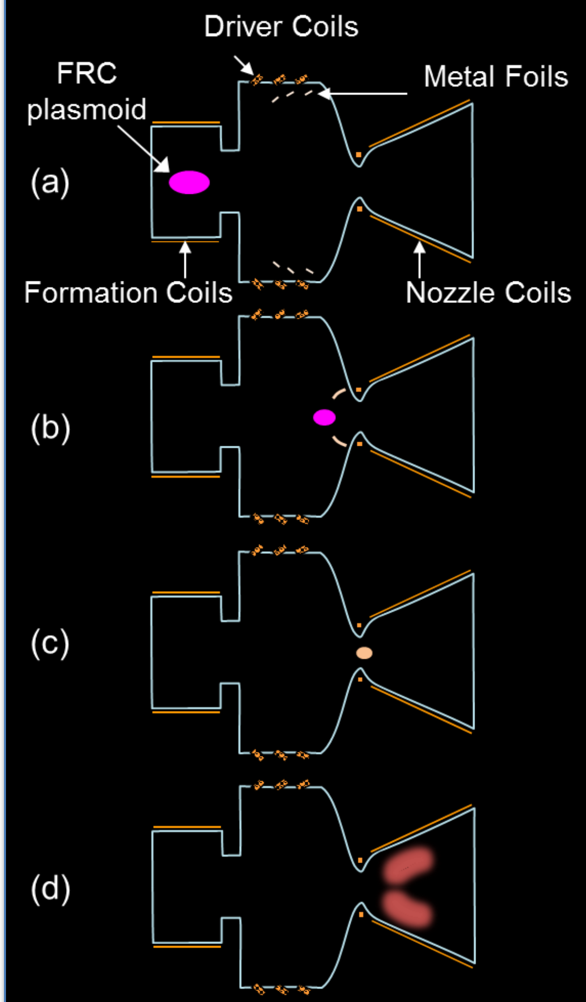
- Governmental support
- Public interest
- Political

Solution: New method of propulsion is needed

Short trip time → High $\frac{\text{Engine Power}}{\text{Spacecraft Mass}}$ (α)

Reduced IMLEO → High Exit Velocity (I_{sp})

The Fusion Driven Rocket



(a) Thin hoops of metal are driven at the proper angle and speed for convergence onto target plasmoid at thruster throat. Target FRC plasmoid is created and injected into thruster chamber.

(b) Target FRC is confined by axial magnetic field from shell driver coils as it translates through chamber eventually stagnating at the thruster throat

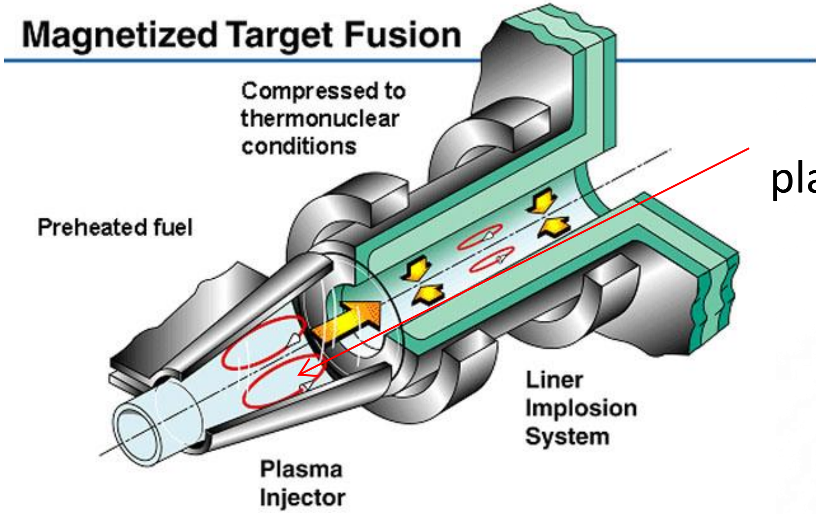
(c) Converging shell segments form fusion blanket compressing target FRC plasmoid to fusion conditions

(d) Vaporized and ionized by fusion neutrons and alphas, the plasma blanket expands against the divergent magnetic field resulting directed flow of the metal plasma out of the magnetic nozzle.

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

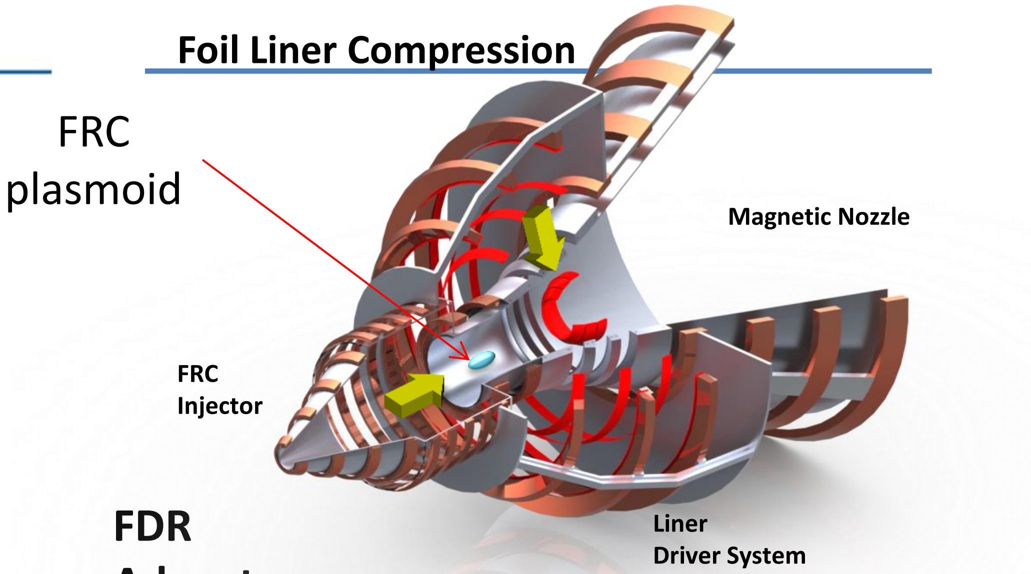
Magneto-Inertial Fusion
Two Approaches

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



FRC plasmoid

Liner implosion from j x B force between external coil and induced liner currents



MTF
Issues:

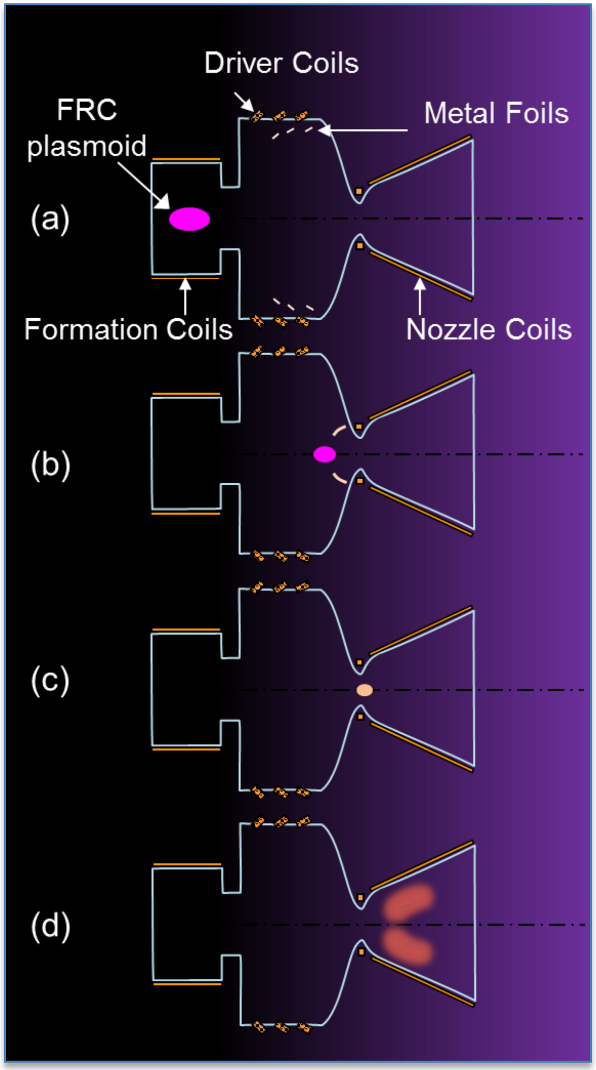
- Extremely low inductance load difficult to drive (massively parallel HV caps and switches)
- Close proximity and electrical contact ⇒ major collateral damage with each pulse
- Small FRC must be formed close to implosion ⇒ marginal B for ignition w injector destruction
- Only inefficient 2D compression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

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

John Slough, David Kirtley, George Votroubek, and Chris Pihl, *"Fusion Based on the Inductively-Driven Lithium Liner Compression of an FRC Plasmoid"*, 20th ANS TOFE, Aug 2012

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	solid propellant	No significant tankage
3	High exhaust velocities (2000-5000s Isp)	Short trip time, high mass fraction Low IMLEO
4	Magnetic insulated nozzle	No significant physical interaction Minimal thermal mass
5	MIF's Low energy requirements	Low mass (single launch) and greatly reduced cost
6	Fusion energy yield has been demonstrated	Fundamental physics is proven and understood

1. Background
2. **Mission Architecture Design**
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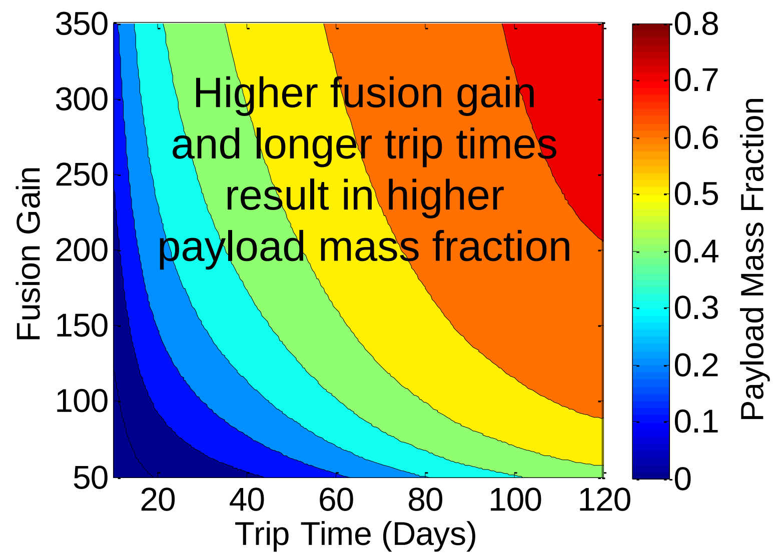
Initial Mission Studies

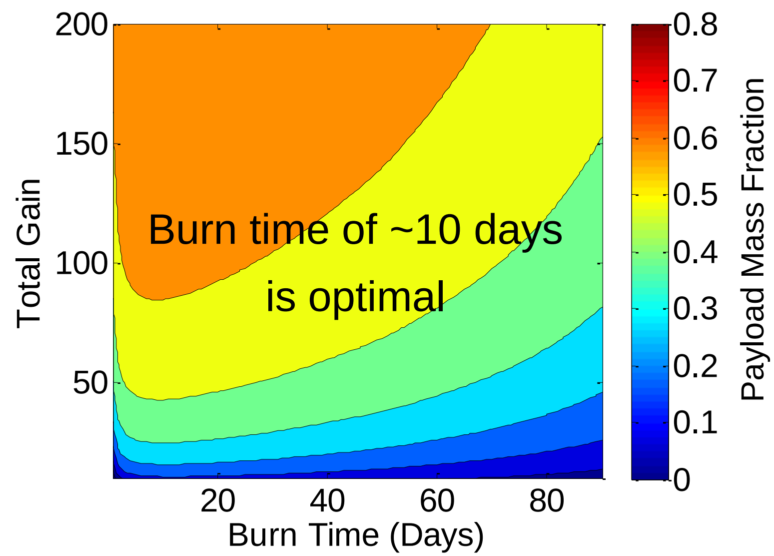
Fusion Assumptions:

- Ionization cost is 75 MJ/kg
- Coupling Efficiency to liner is 50%
- Thrust conversion η_t ~ 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: $G_F = G_F$(calc.)/2

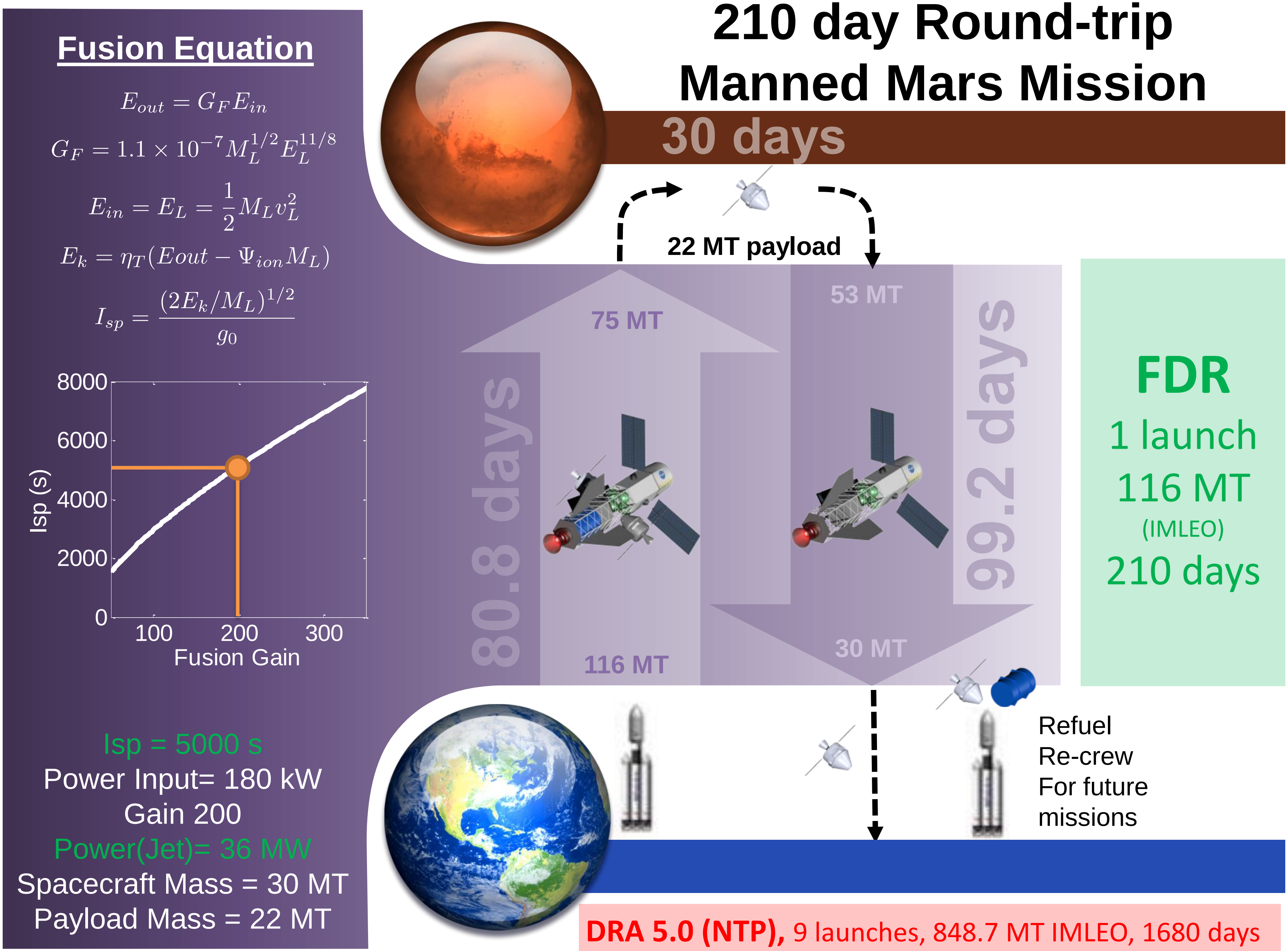
Mission Assumptions:

- Mass of Payload= 61 MT
  - Habitat 31 MT
  - Aeroshell 16 MT
  - Descent System 14 MT
- Specific Mass of capacitors ~ 1 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





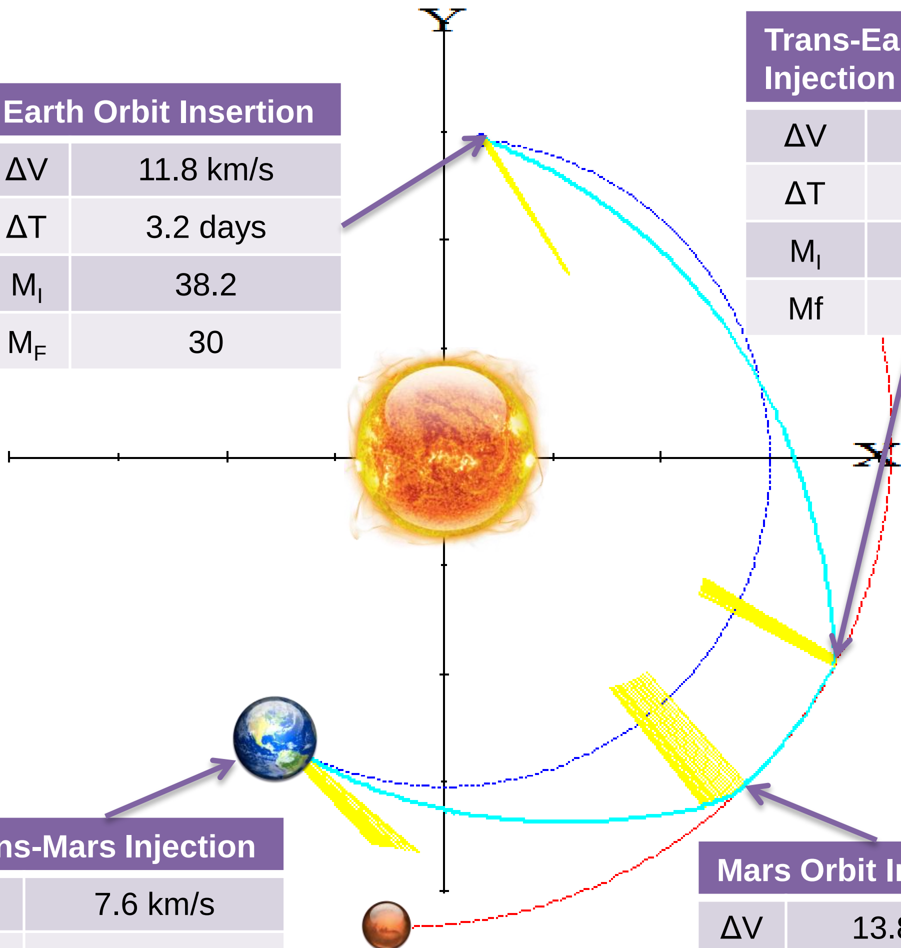
Anthony Pancotti, John Slough, David Kirtley, Micheal Pfaff, Christopher Pihl, George Votroubek, *"Mission Design Architecture for the Fusion Driven Rocket"*, AIAA 48th JPC, July 2012


210 day Round-trip
Manned Mars Mission
Fusion Equation
$E_{out} = G_F E_{in}$
$G_F = 1.1 \times 10^{-7} M_L^{1/2} E_L^{11/8}$
$E_{in} = E_L = \frac{1}{2} M_L v_L^2$
$E_k = \eta_T (Eout - \Psi_{ion} M_L)$
$I_{sp} = \frac{(2E_k/M_L)^{1/2}}{g_0}$
8000
6000
4000
2000
0
Isp (s)
100
200
300
Fusion Gain
Isp = 5000 s
Power Input= 180 kW
Gain 200
Power(Jet)= 36 MW
Spacecraft Mass = 30 MT
Payload Mass = 22 MT
30 days
22 MT payload
75 MT
53 MT
80.8 days
99.2 days
116 MT
30 MT
FDR
1 launch
116 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)

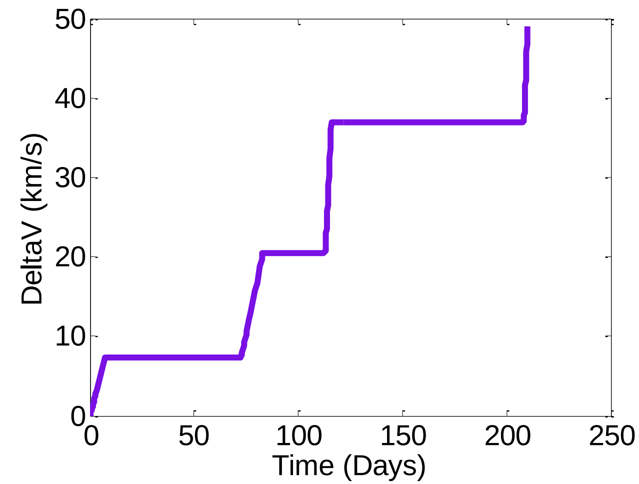
Earth Orbit Insertion	
ΔV	11.8 km/s
ΔT	3.2 days
M_I	38.2
M_F	30

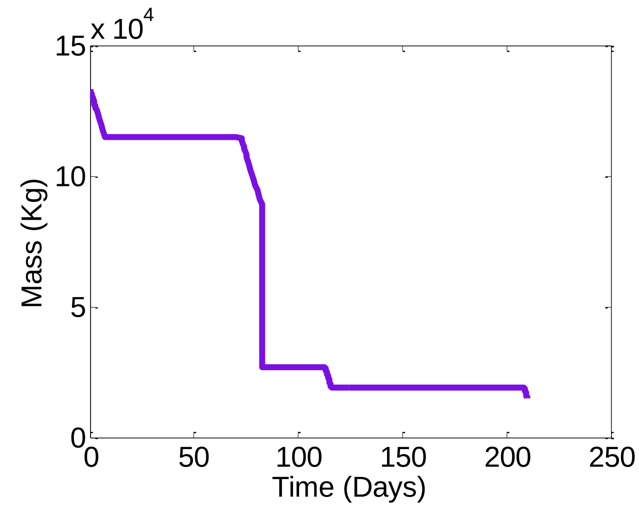
Trans-Earth Injection	
ΔV	16.2 km/s
ΔT	5.8 days
M_I	53.1
Mf	38.2



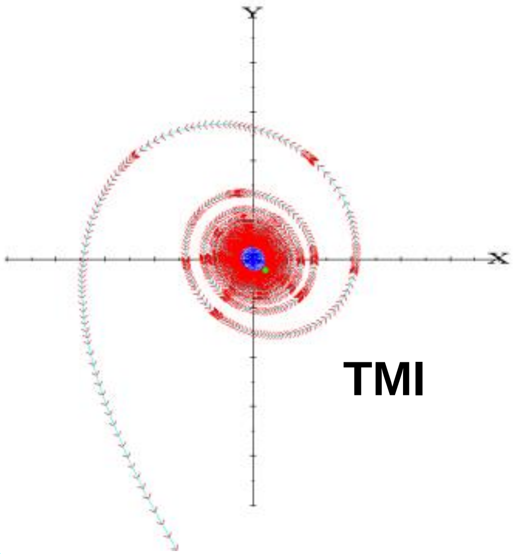
Trans-Mars Injection	
ΔV	7.6 km/s
ΔT	6.5 days
M_I	116.4
Mf	99.6

Mars Orbit Insertion	
ΔV	13.8 km/s
ΔT	9.5 days
M_I	99.6
Mf	75.1

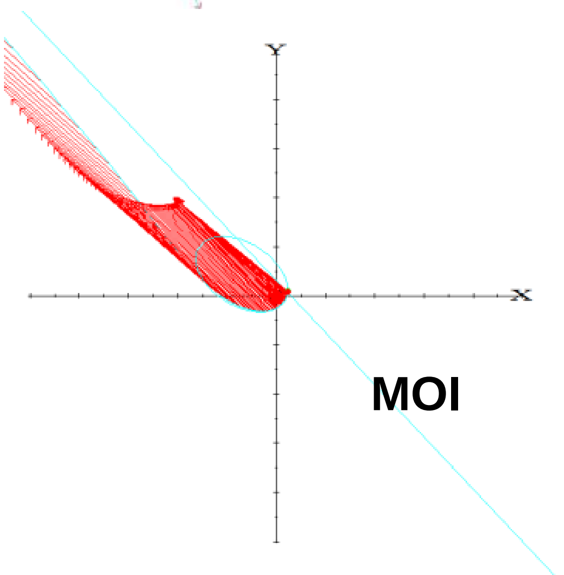


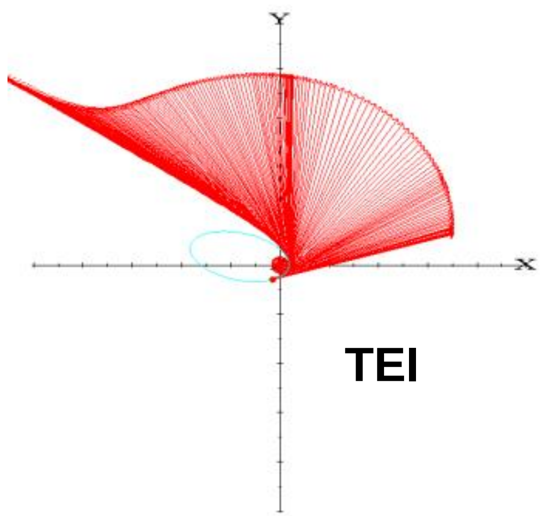


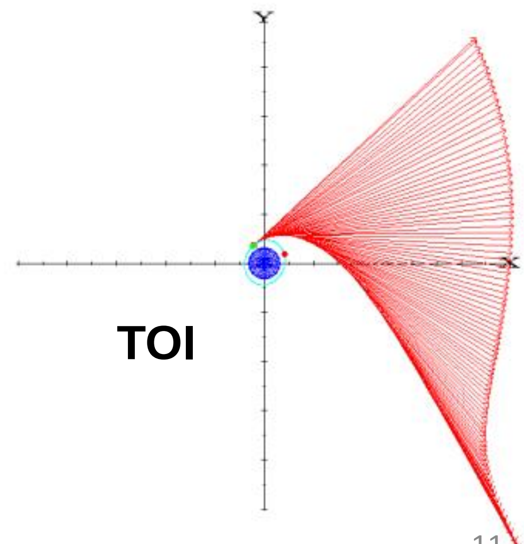
Near Body Maneuvers



Maneuver	ΔV (km/s)		ΔT (days)	
	Near Body	Simplified	Near Body	Simplified
TMI	12.7	7.6	8.9	6.5
MOI	8.5	13.8	4.7	9.5
TEI	16.6	16.2	1.7	5.8
EOI	11.2	11.8	1.6	3.2
Total	**49.0**	**49.0**	**16.8**	**22.1**







1. Background
2. Mission Architecture Design
3. **Spacecraft Design**
4. Fusion Physics

Spacecraft Scaling

Mission Assumptions		
Payload mass	22	MT
Spacecraft mass	30	MT
IMLEO	<130	MT
Earth Orbital Altitude	407	km
Mars park orbit	1	sol
	250 x 33793	km
Total Mission Time	210	days
Stay Time	30	days

Mission Architecture Design

Propulsion Requirements		
Isp	5000	s
Jet Power	36	MW
Specific Power	240	W/kg

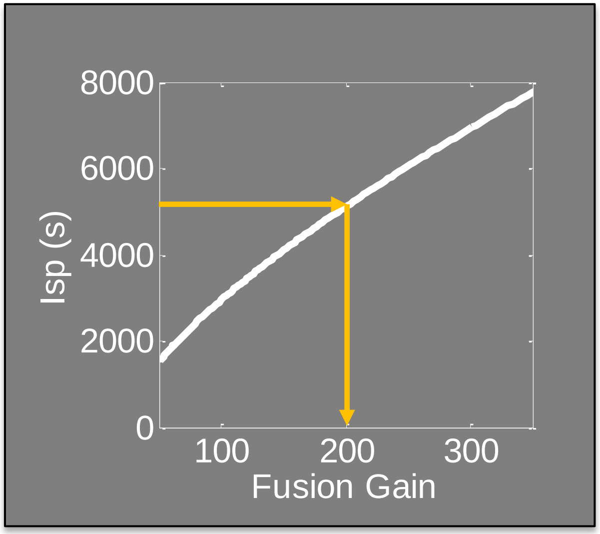
$$E_{out} = G_F E_{in}$$

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

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

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

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



Power System Scaling

ENERGY STORAGE

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

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

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

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

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

Gain of 200

2.4 MJ Input Energy @ 2J/g

1.2 MT of Capacitors

50% space de-rating

1.8 MT of Energy Storage

POWER SOURCE

Solar panels have flown on 99% of all space mission.

$\frac{\text{36 MW Jet Power}}{\text{Gain of 200}}$ → 180 kW of Input power OR 400 kW at Mars

200 W/kg

2 MT of Solar Panels

500 w/kg to 1000 kg have speculated for future
Direct energy recovery from fusion reaction possible

Mass Budget

Spacecraft Component	Mass (MT)
Energy storage[3]	1.8
Solar Panels[6]	2.0
Switches and cables[5]	1.8
Spacecraft structure[1]	3.8
Lithium containment vessel	0.1
FRC Formation[2]	0.2
Propellant Feed mechanism	1.2
Liner driver coils[4]	0.3
Thermal Management	1.1
Magnetic Nozzle	0.2
Margin	2.5
Spacecraft Mass	**15**
Crew habitat (DRA5.0)	39
Lithium Propellant	62
Total Mass	**116**

Payload mass fraction 47%

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

Switches and cables equal to energy storage mass

Simple aluminum coil, but most likely composites with tungsten or beryllium

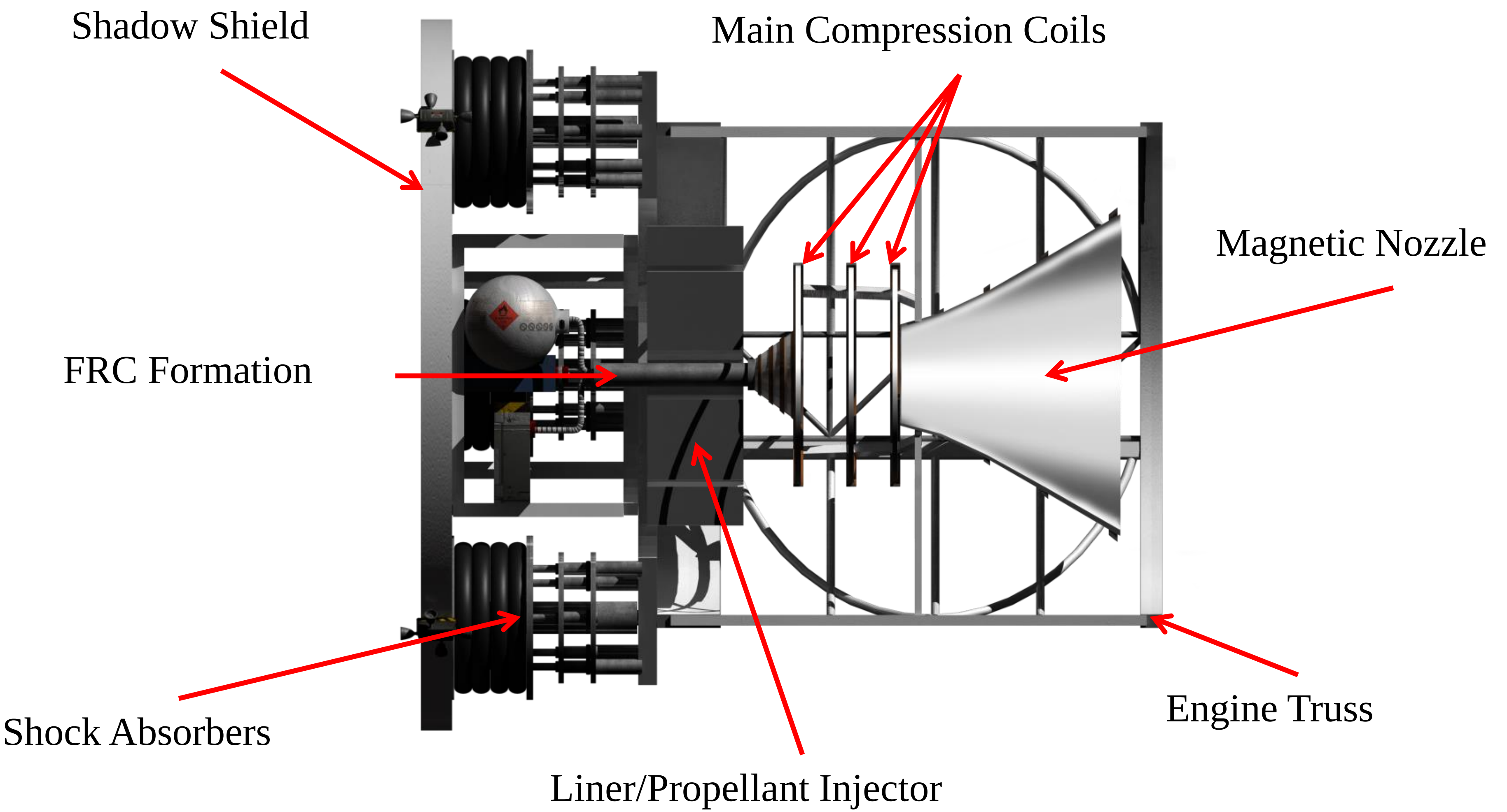
Thermal control, 10% heat rejection @ 1 kW/kg with a margin of 3X

FRC formation based of lab equipment

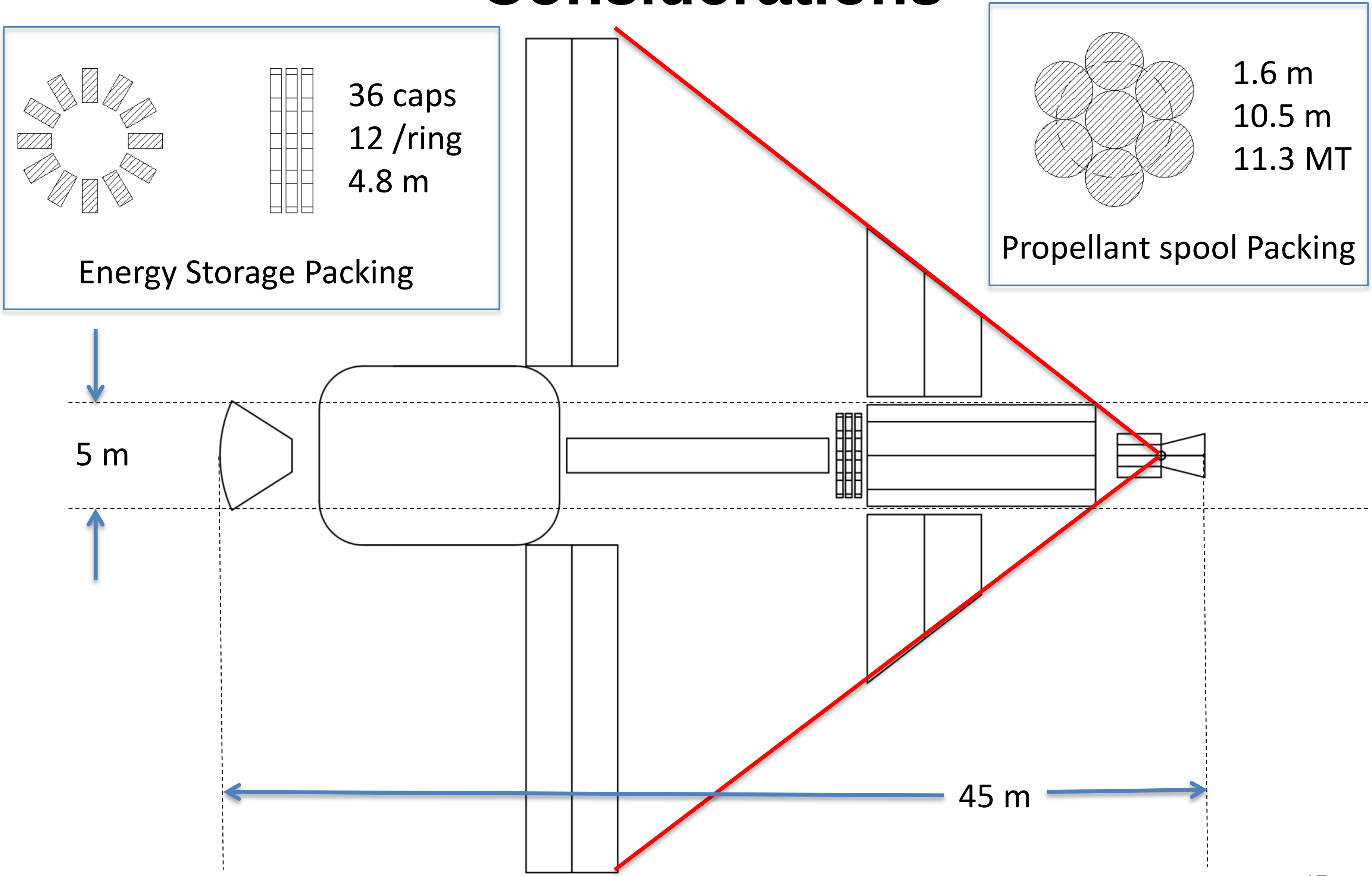
Propellant Feed – roll of film – ring formation and injection

20% Margin

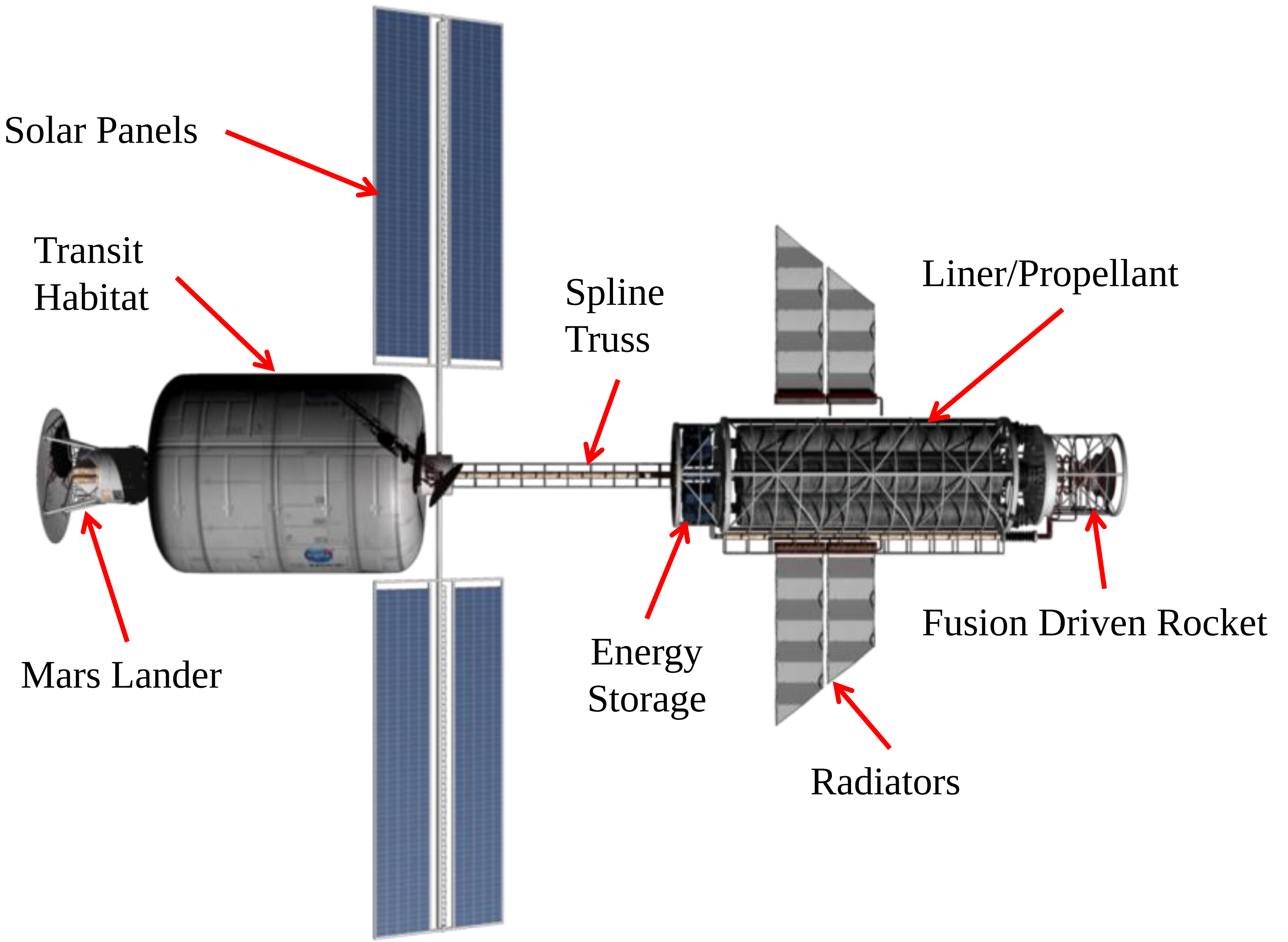
Fusion Driven Rocket Engine



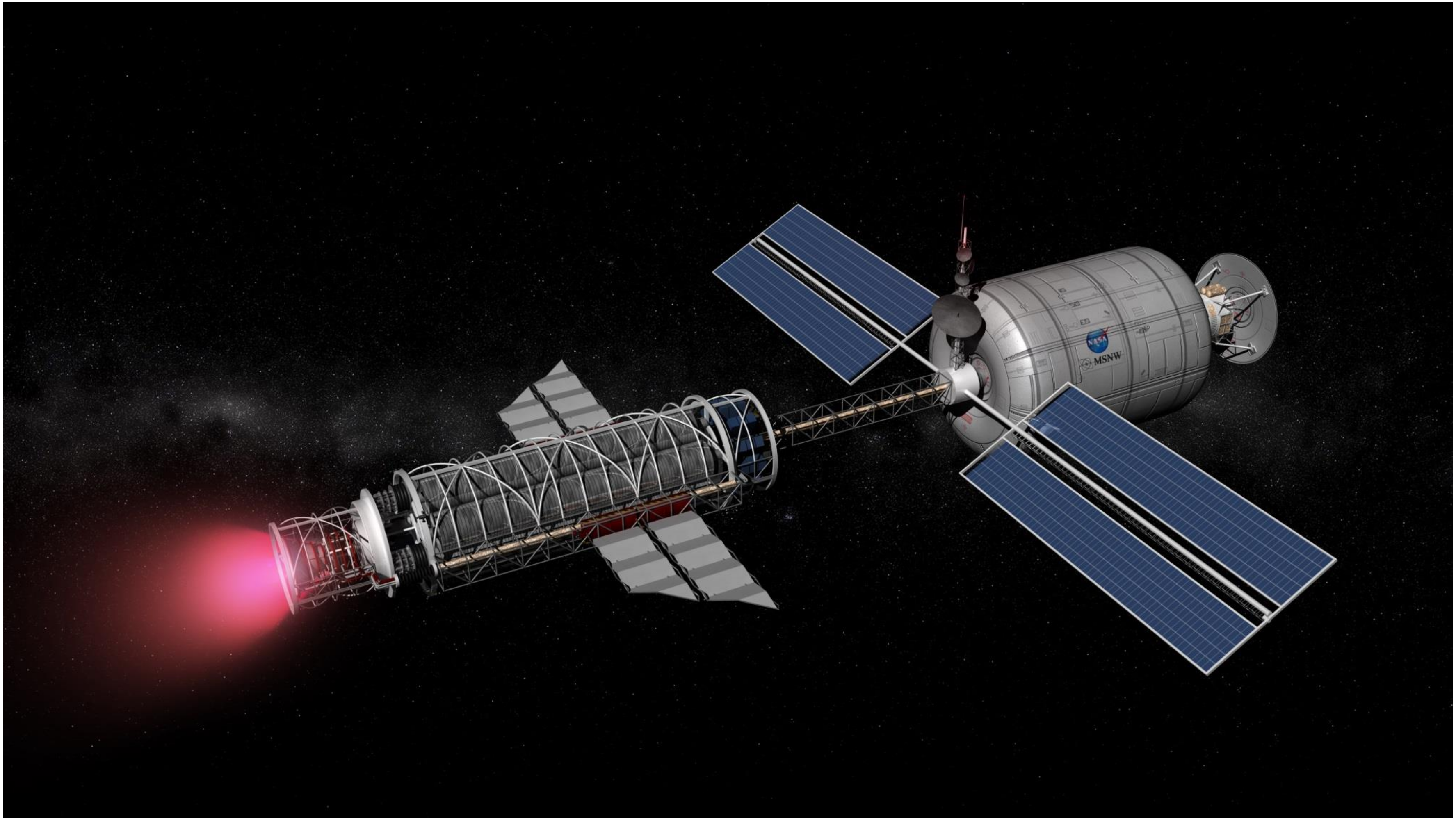
Spacecraft Layout Considerations



FDR Spacecraft Layout



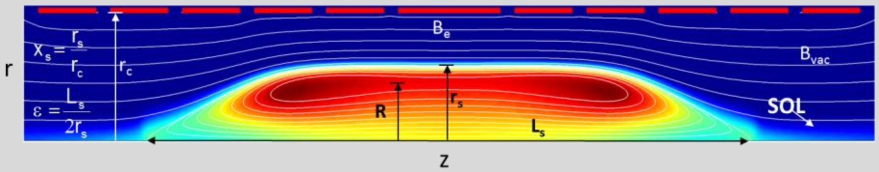
Final Spacecraft Design



1. Background
2. Mission Architecture Design
3. Spacecraft Design
4. **Fusion Physics**

Fusion Approach

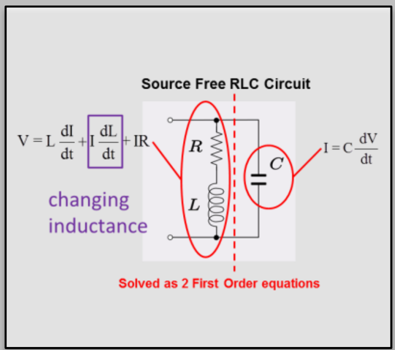
1. Analytical

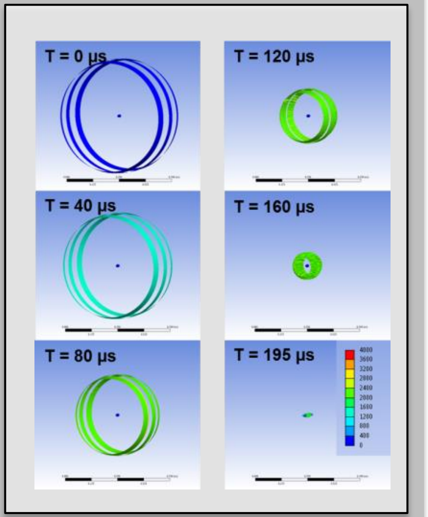


$$E_{fus} \cong 1.2\times10^{-12}\, n_0^2 \langle\sigma v\rangle \frac{4}{3}\pi r_0^3\, \varepsilon\, \tau_D = 1.1\times10^{-42}\, n_0^2 T_0^2 \frac{r_0^4}{v_L}\varepsilon$$

$$E_L = \frac{1}{2} M_L v_L^2 = 3 n_0 k T_0 \cdot \frac{4}{3}\pi r_0^3 \varepsilon = \frac{B_0^2}{\mu_0}\pi r_0^3 \varepsilon$$

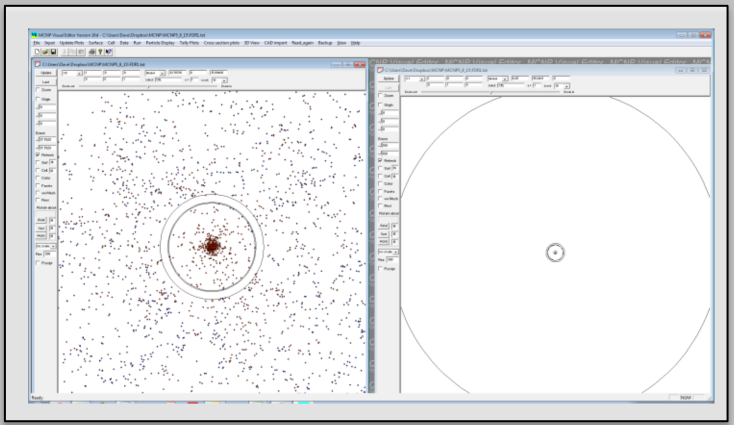
$$G = \frac{E_{fus}}{E_L} = 1.73\times10^{-3}\sqrt{\frac{M_L}{l_0}}\, B_0 = 4.3x10^{-8} M_L^{1/2} E_L^{11/8}$$





2. Computational

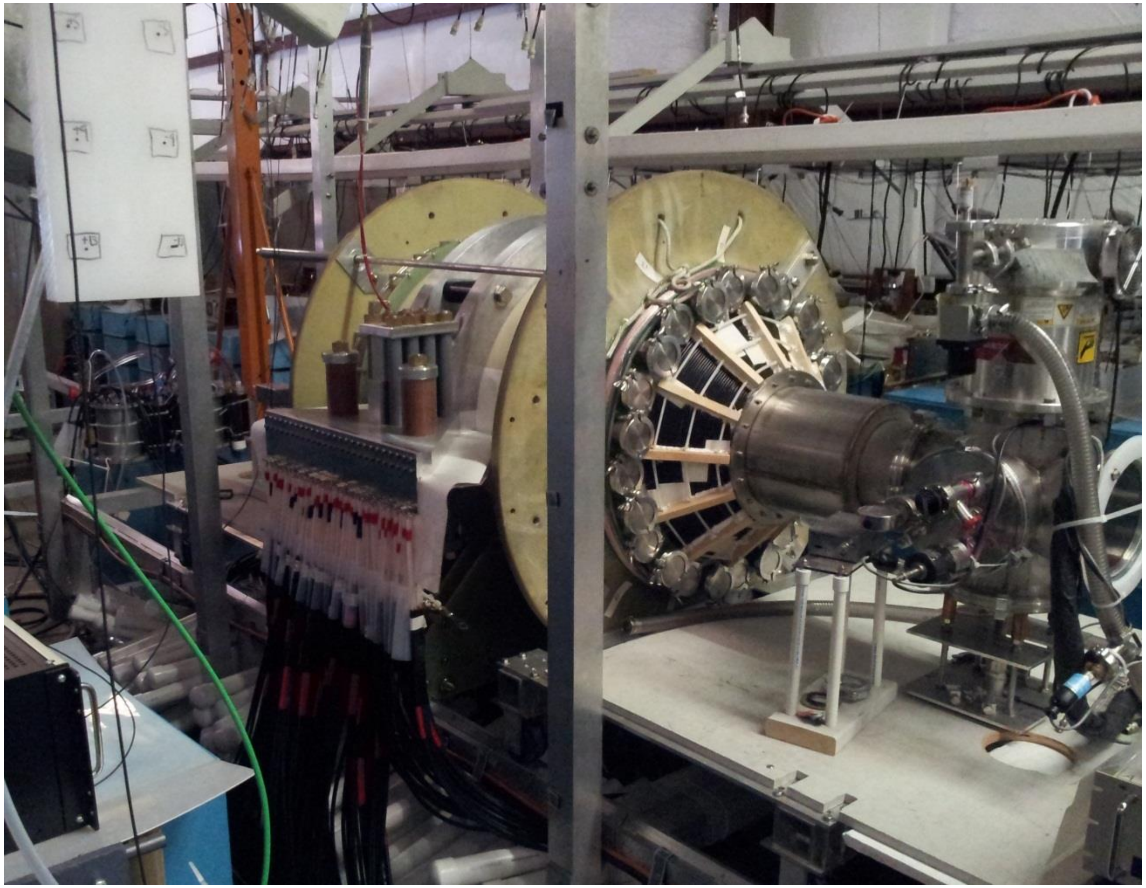
- 1D Liner Dynamic + Circuit
- 3D Structural compression
  - (ANSYS)
- Neutronics



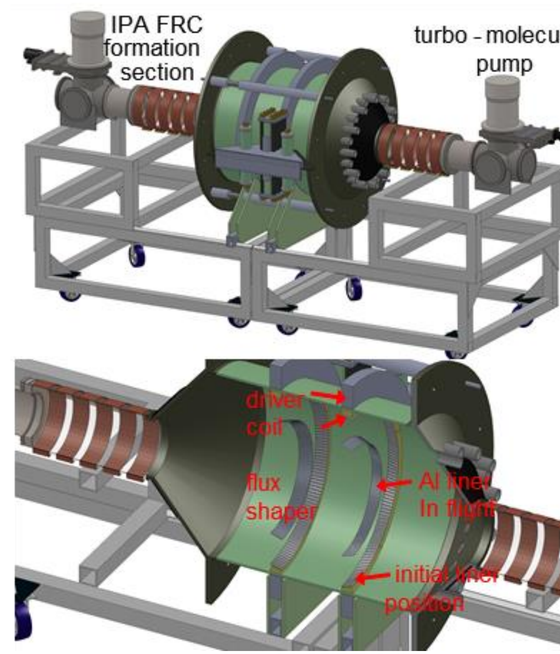
3. Experimental Validation

Expirmental

IDL Validation Experiment at MSNW

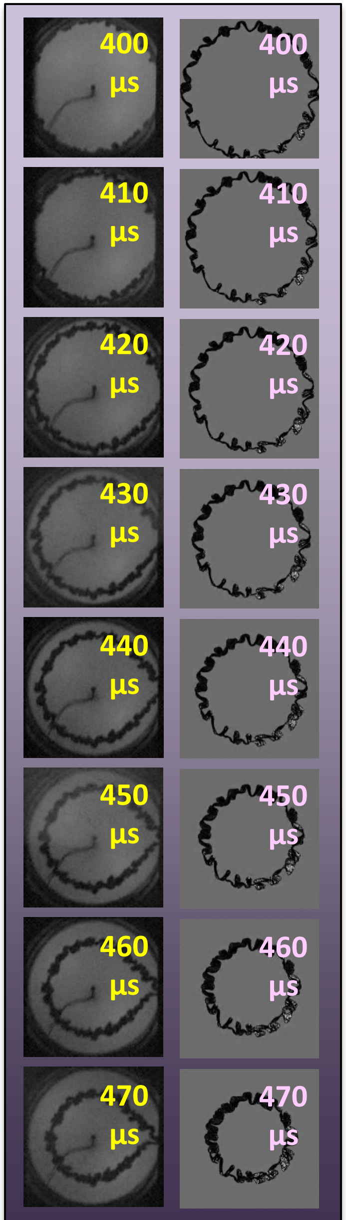


Picture of the FDR validation experiment construction now underway.



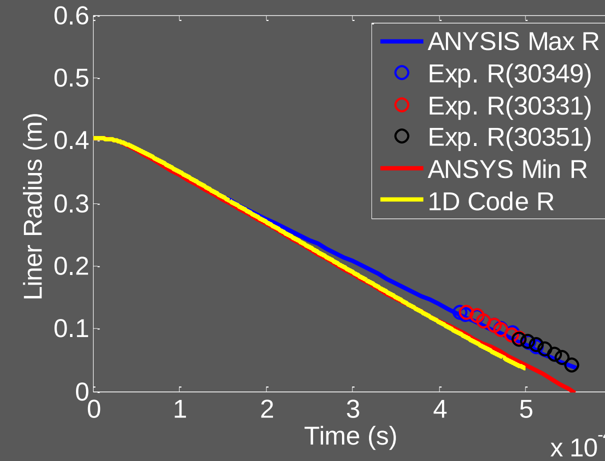
CAD rendering of the Foil Liner Compression (FLC) test facility at MSNW

Experimental Results

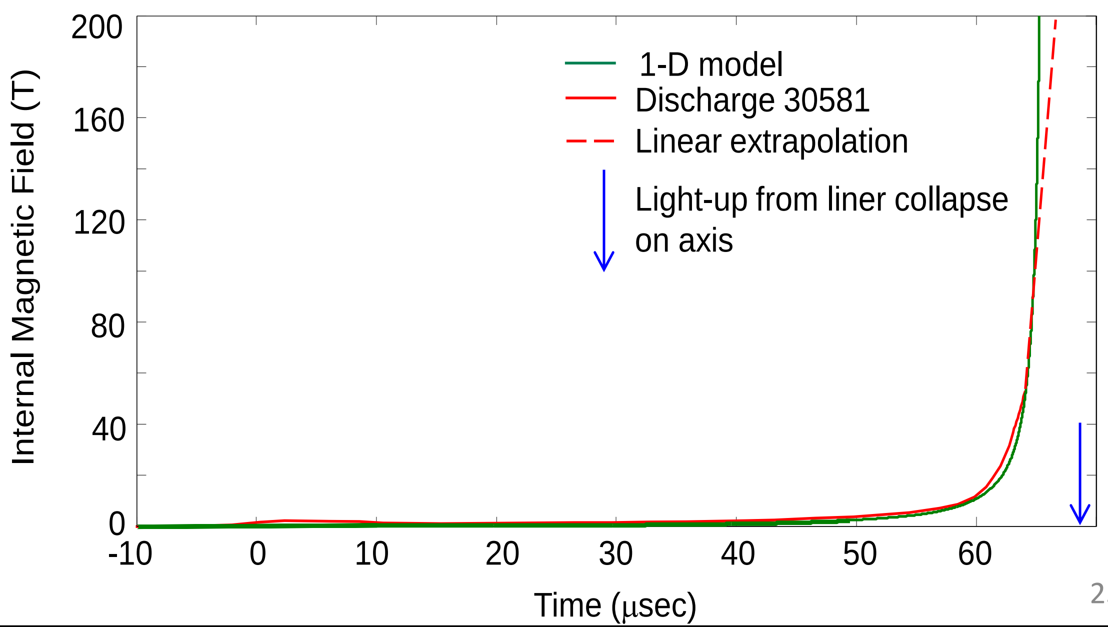


¼ Power Aluminum Liner Testing for code Validation

40 cm
6 cm
0.4mm
20 kV
840 µF



10.3 cm
5 cm
0.4 mm
20 kV
840 µF



Summary

Mission Architecture Goal
90 Transit times to and from Mars
Single launch to Mars (130 MT IMLEO)
No pre-deployed assets
63 MT Payload mass
Full propulsive MOI
Full propulsive EOI
Reusable spacecraft

Mission Assumptions		
Payload mass	63	MT
Spacecraft mass	15	MT
IMLEO	130	MT
Earth Orbital Altitude	407	km
Mars park orbit	1	sol
Total Mission Time	210	days
Stay Time	30	days

Propulsion Requirements		
Isp	5000	s
Jet Power	36	MW
Specific Power	240	W/kg
Gain	200	

FDR is Finishing Phase 2 NIAC

- Mission architecture
- Spacecraft Design
- Fusion Physics
  - Analytical
  - Computational
  - Experimental

Backup Slides

Determining the Optimal Mars Mission

Opposition-class
- short surface stay times at Mars
  - typically 30 to 90 days
- relatively short total round-trip mission times
  - 500 to 650 days

Conjunction-class
- long-duration surface stay times
  - 500 days or more
- long total round-trip times
  - approximately 900 days
- minimum-energy solutions for a given launch opportunity

Both options are well outside the current permissible exposure limit of radiation

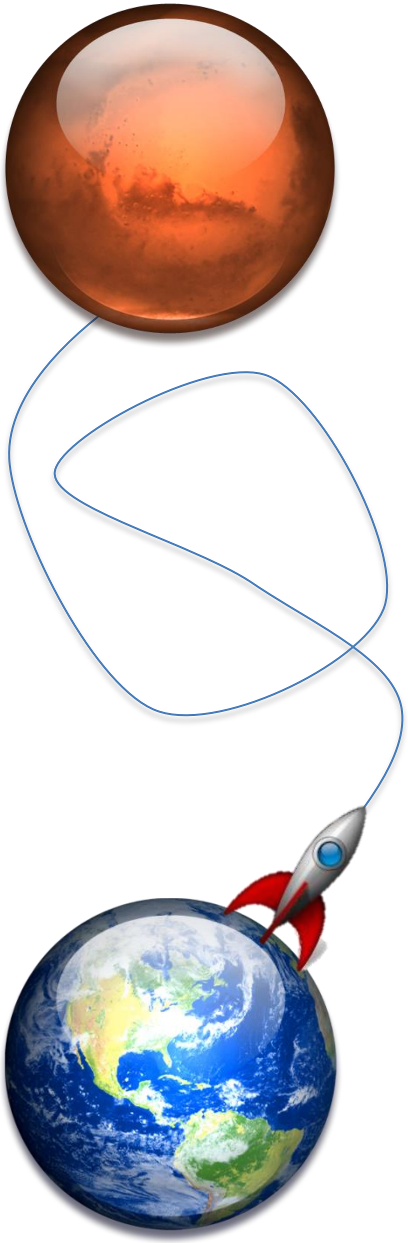
(1) shortest overall mission to reduce the associated human health and reliability risks
(2) adequate time on the surface in which to maximize the return of mission objectives and science
(3) low mission mass, which, in turn, reduces the overall cost and mission complexity

"ideal mission does not exist"

Mission down design approach

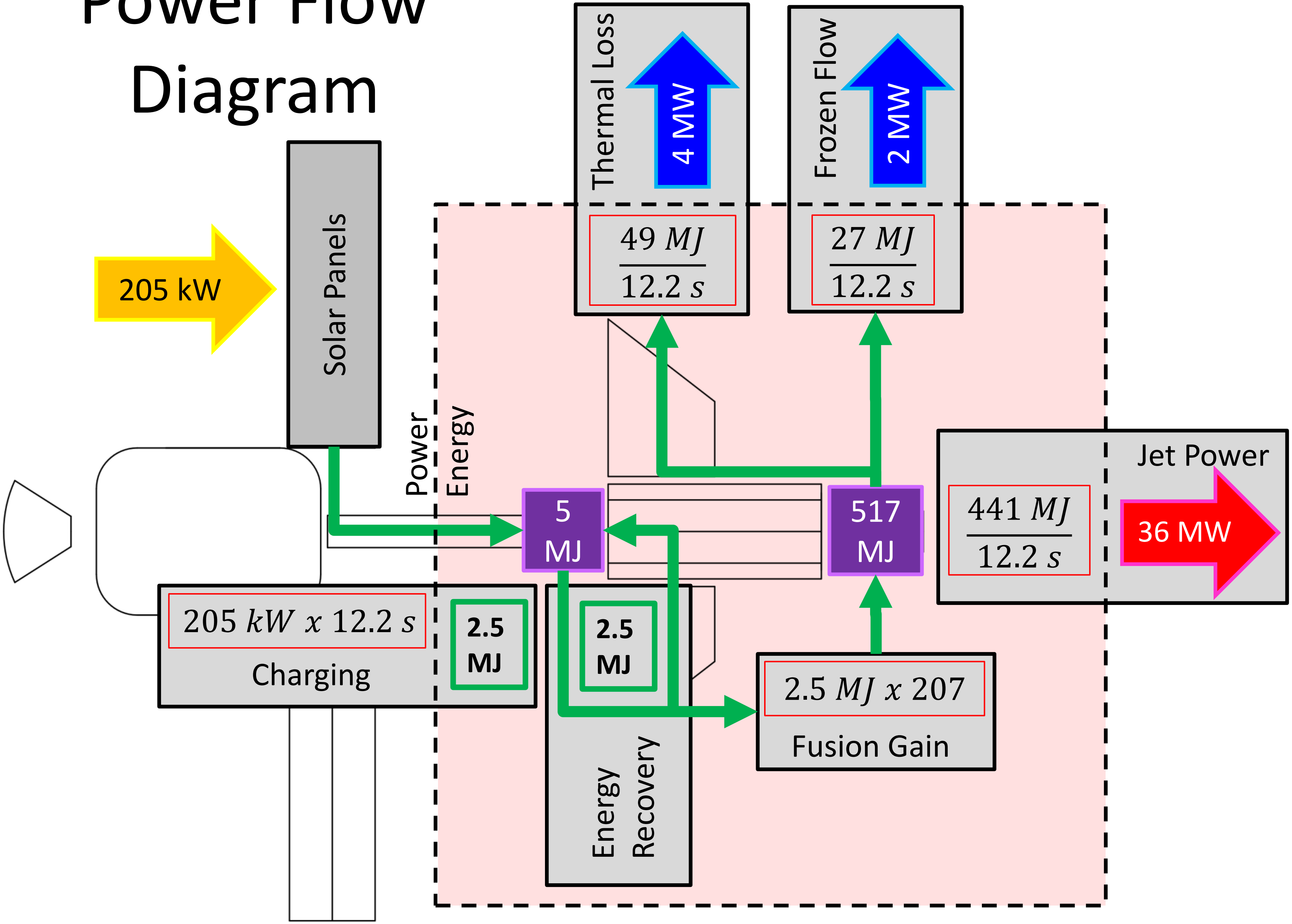
Mission Architecture Goal
90 Transit times to and from Mars
Single launch to Mars (<130 MT IMLEO)
No pre-deployed assets
22 MT Mars Payload mass
Full propulsive MOI
Full propulsive EOI
Reusable spacecraft

Future Mission Studies



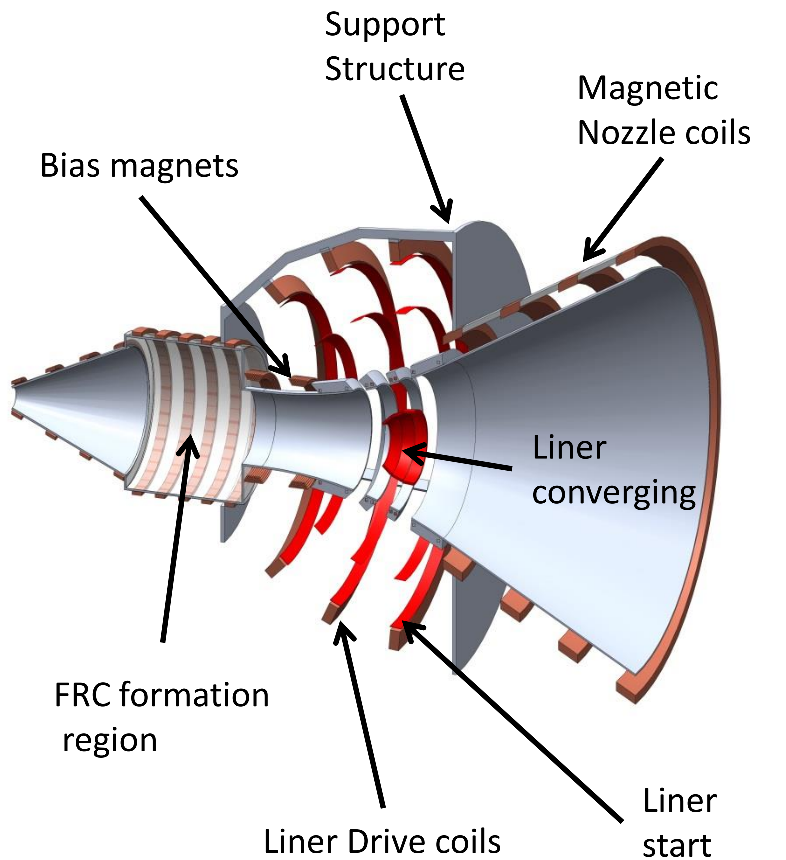
- **Mars**
  - Single launch to Mars (Opposition Class)
    - Mission refinement
  - Long Stay Mission (>500 day) (Conjunctive Class)
  - Single trip – on orbit assembly
    - Larger s/c (fuel launched separate)
  - Pre-deploy mission architecture
    - Classic DRA style with pre-curser cargo mission
  - Ultra-fast (30 day) transfers
- **Jupiter**
  - Enter and exit gravity well
  - Moon mission
- **NEO**
  - Sample return
  - Redirection?

Power Flow Diagram



Future Design work

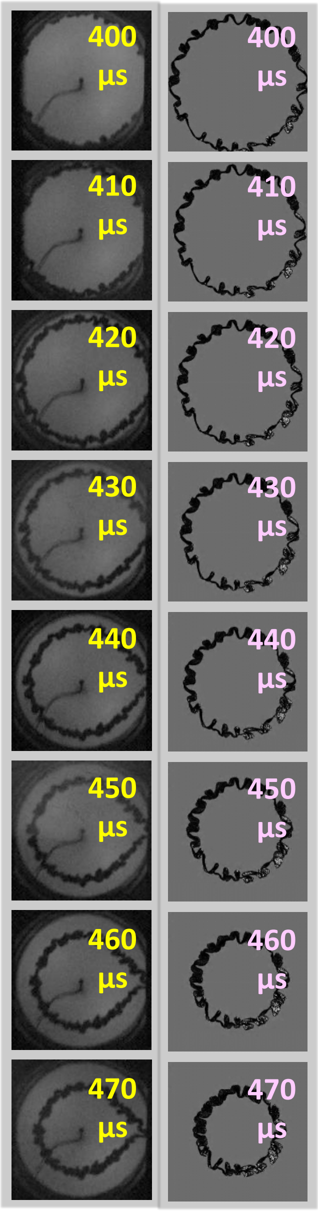
Spacecraft Component	Mass (MT)	TRL	Mission Dependent	Fusion Dependent
Spacecraft structure	3.8	4	X	
Propellant tank	0.1	5	X	X
FRC Formation	0.2	4		X
Propellant Feed	1.2	2		X
Energy storage	1.8	7		X
Liner driver coils	0.3	3		X
Switches and cables	1.8	6		X
Solar Panels	2.0	8	X	X
Thermal Management	1.1	5		X
Nozzle	0.2	2		X
Margin	2.5			
Spacecraft Mass	**15**		**X**	**X**
Crew habitat	61		X	
Propellant	56		X	X
Total Mass	**134**		**X**	**X**



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

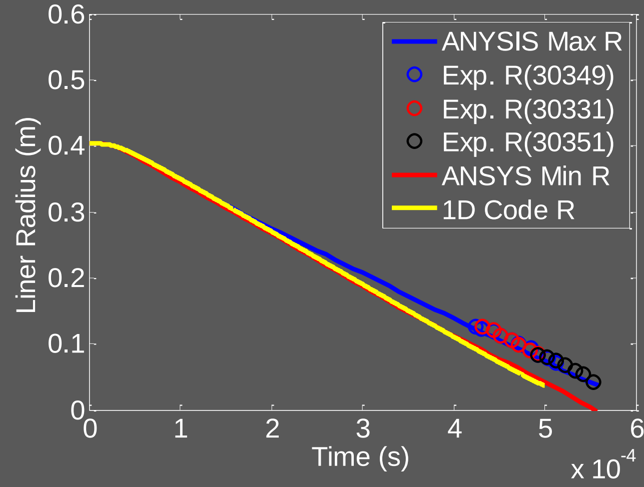
Experimental Results

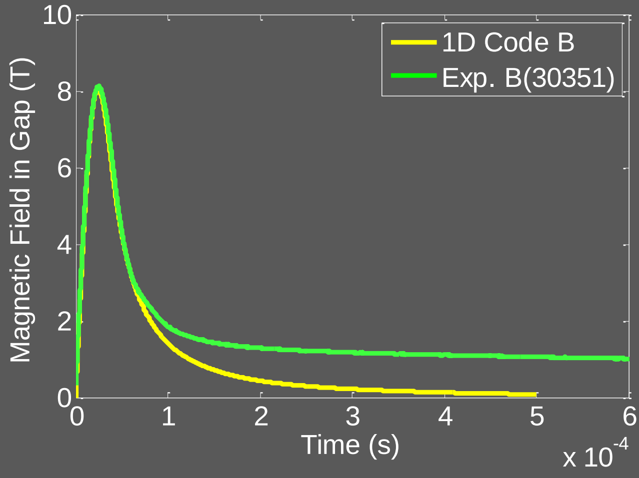
40 cm radius, 6 cm wide, 0.4 mm thick Aluminum liners

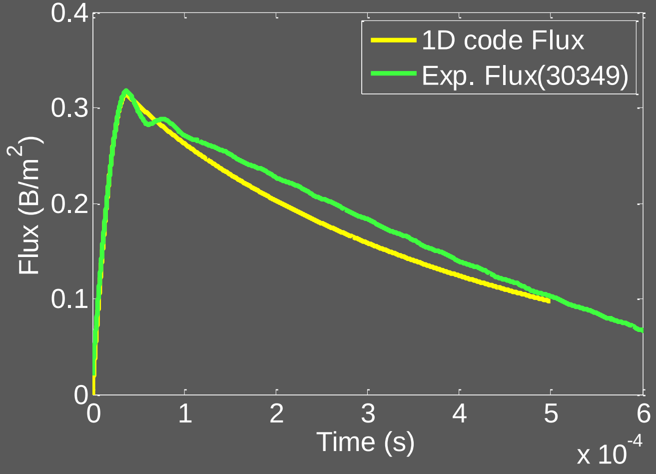


¼ Power Aluminum Liner Testing for code Validation

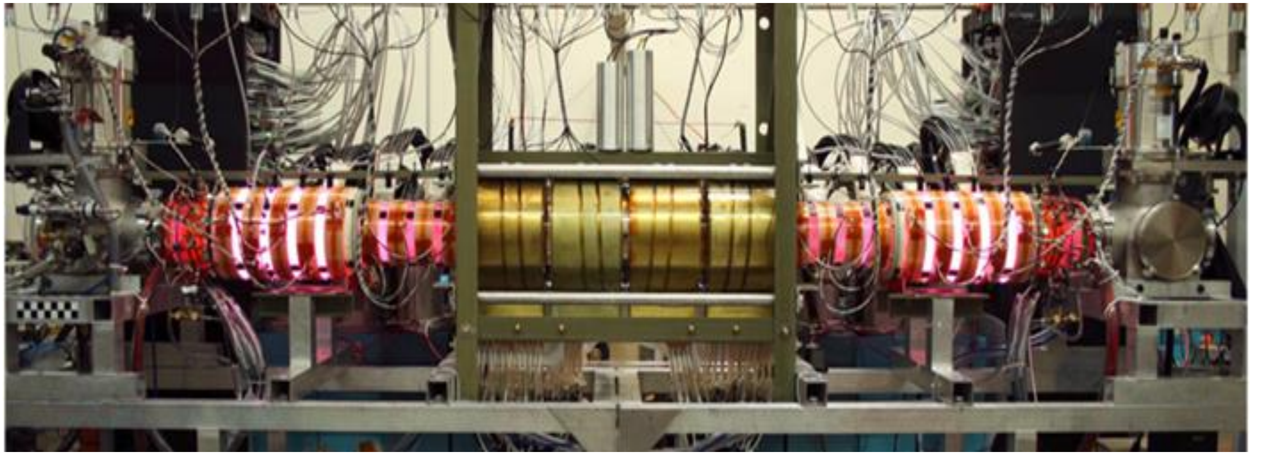
20 kV | 840 µF | 16 mil







FRC Fusion at MSNW



"Creation of a High Temperature Plasma through Merging and Compression of Supersonic Field Reversed Configuration Plasmoids" . Journal of Nuclear Fusion, 2011

- Fusion with this technique is proven
- $5 M DOE-funded programs demonstrated high field compression of FRC to fusion conditions
  - 2.3 keV Deuterium Ions
  - >100 microsecond lifetimes of 1E22 plasma
  - >1E12 D-D neutrons created in this program
  - At only 1.2 Tesla!
- FRC programs at similar size demonstrated >3 ms lifetime

Anticipated Parameters from FDR Validation Experiment

FRC adiabatic scaling laws

Adiabatic Law:	$P \sim V^{-5/3}$	$T \sim B_e^{4/5}$
Rad. P Balance:	$P \sim nkT \sim B_e^2$	$n \sim B_e^{6/5}$
Particle Cons:	$nV = \text{const.}$	$r_s^2\, l_s \sim B_e^{-6/5}$
FRC φ Cons:	$\varphi \sim r_c^2\, B_e$ (const x_s)	$l_s \sim r_s^{2/5}$

(The four laws together $\Rightarrow$ the four scaling results.)

Parameter	Merged FRC ($t = \tau_{1/4}$)	Radial FRC Compression	Axial FRC Compression
v_L (km/s)	2.5	~ 0	0
r_L (cm)	22.5	0.9	0.9
r_s (cm)	20	0.8	0.88
l_s (cm)	80	22	3.5
B_{ext} (T)	0.16	100	410
T_e+T_i (keV)	0.06	5	15
n (m^{-3})	1.1×10^{21}	2.5×10^{24}	1.4×10^{25}
E_p (kJ)	2.2	180	560
E (Pa)	1.5×10^4	6×10^9	10^{11}
τ_N (µs)	600	175	270

Initial FRC size, temp density and energy sam as past FRC's

FRC lifetime $>> \tau_{dwell} \sim 4\ \mu s$

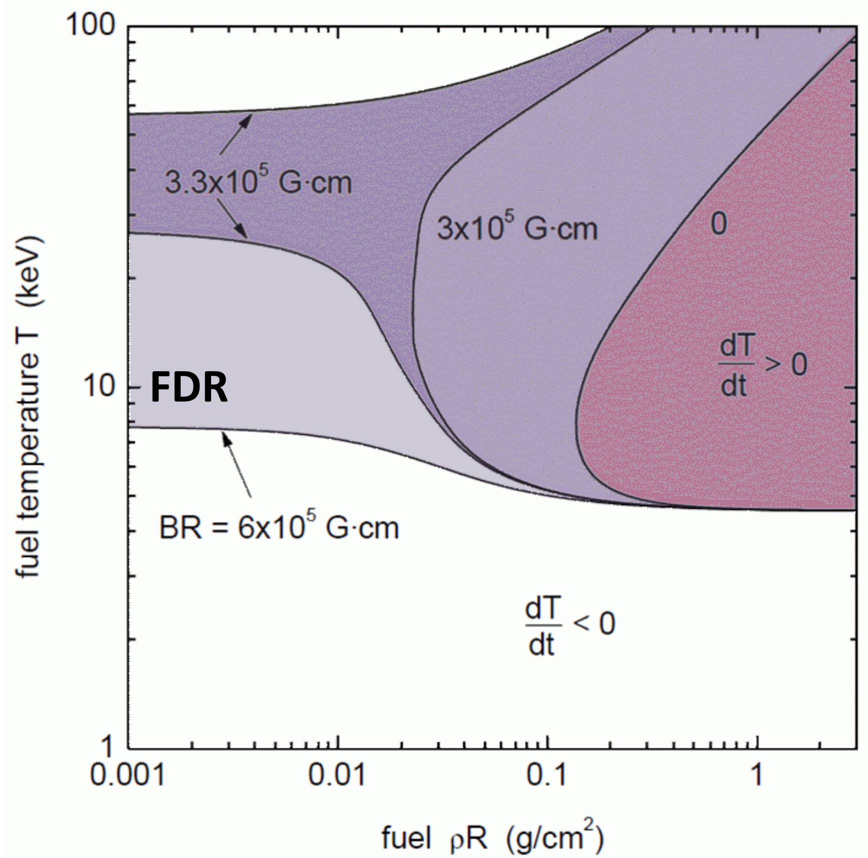
In experiment, FRC radial and axial compressions would occur simultaneously

Final field similar to that achieved in several flux compression expts.

Sub MJ FRC Requires only 33% bank eff.

- Final FRC parameters yield a fusion gain **G = 1.6** (M_L=0.18 kg Al)

Lindl-Widner Diagram with Magnetic Field Confinement Of the Fusion Alphas

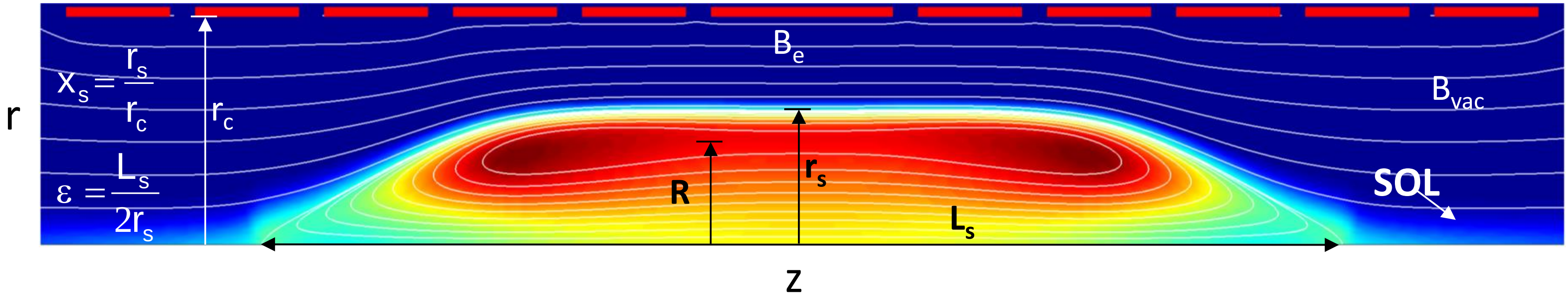


The BR form of the L-W diagram. Ignition curves for different product BR.

When the BR parameter exceeds the threshold value, the dT/dt > 0 region extends to infinitely small ρR and ignition becomes possible at any ρR.

Field Reversed Configuration (FRC)

Magnetic Field lines and Pressure Contours



Key Equilibrium Relations:

$$B_{ext} = \frac{B_{vac}}{1 - x_s^2}$$

$$P_0 = n_0 kT = \frac{B_{ext}^2}{2\mu_0}$$

$$\langle \beta \rangle = 1 - \frac{1}{2} x_s^2$$

Flux Conservation

External measurements of B yield
FRC separatrix radius $r_s(z)$, FRC length L_s
$\Rightarrow$ volume, position, velocity

Radial Pressure Balance

Simple cross-tube interferometric measurement with r_s from yields $\langle n \rangle$ and T

Axial Pressure Balance

With above obtain plasma energy, Inventory, confinement times

FRC equilibrium constraints and the diagnostic measurements that together with the equilibrium relations that are employed to determine the basic parameters of the FRC equilibrium

Fusion Based on Inductively Driven Liner 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_0, so that one can write:

$$E_L = \frac{1}{2} M_L v_L^2 = 3 n_0 k T_0 \cdot \frac{4}{3} \pi r_0^3 \varepsilon = \frac{B_0^2}{\mu_0} \pi r_0^3 \varepsilon \qquad (1)$$

The zero subscript indicates values at peak compression where $r_s \sim r_0$ and magnetic pressure balance ($2n_0kT_0 = B_0^2 / 2\mu_0$).

Fusion energy produced in the FRC during the liner's dwell time τ_D at peak compression:

$$E_{fus} \cong 1.2 \times 10^{-12} n_0^2 \langle \sigma v \rangle \frac{4}{3} \pi r_0^3 \varepsilon \tau_D = 1.1 \times 10^{-42} n_0^2 T_0^2 \frac{r_0^4}{v_L} \varepsilon \qquad (2)$$

where n_0 and T_0 are the peak density and temperature, and where the liner shell dwell time at peak compression, τ_D, ~ $2r_0/v_L$

Fusion Based on Inductively Driven Liner Compression of the FRC (cont.)

The usual approximation for the D-T fusion cross section in this temperature range: $\langle \sigma v \rangle \cong 1.1\text{x}10^{-31}\ T^2(\text{eV})$ was also assumed. Pressure balance, together with expressions (1) and (2) yields for the fusion gain:

$$G = \frac{E_{fus}}{E_L} = 1.73\times10^{-3}\sqrt{\frac{M_L}{l_0}}\,B_0 = 4.3x10^{-8}\,M_L^{1/2}\,E_L^{11/8} \qquad (3)$$

where l_0 (= $2r_0\cdot\varepsilon$) is the length of the FRC at peak compression. The last expression is obtained from adiabatic scaling laws $\Rightarrow$

$$E_L \sim B_0^2\, r_0^2\, l_0 \sim B_0^{4/5} \quad \text{and} \quad l_0 \sim r_0^{2/5} \sim B_0^{-1/5} \qquad (4)$$

to express G in terms of the liner kinetic energy E_L and mass M_L only.

Fusion Ignition will amplify gain by large factor. It is estimated that the total fusion gain $G_F \sim 5\text{-}10\cdot G$. For a large margin of safety, it is assumed that:
$G_F = 2.5G$ or,

$$\mathbf{G_F = 1.1\times10^{-7}\, M_L^{1/2}\, E_L^{11/8}}$$

Material Constraints with Inductively Accelerated Liners

- The material properties relating to this resistive heating (electrical conductivity, melting point, heat capacity, etc.) can be characterized by a parameter g_M defined by the “current integral”:

$$\int_0^{t_m} I^2\, dt = g_M\ A^2$$

I - current flowing through the material cross-sectional area

A = w×δ, where w is the liner width and δ is the liner thickness.

- The driving force is simply the magnetic pressure ($B^2/2\mu_0$) applied over the surface area of the metal facing the coil when in close proximity to the driving coil.
- The current can be related to the force through Ampere’s law which can be reasonably approximated as $B = \mu_0 I/w$.

One finds for the maximum velocity for a given shell thickness δ:

$$v_m(m/s) = 2.5x10^4\ \delta_{Al}\ (mm) - Aluminum\ 6061$$

$$v_m(m/s) = 1.6x10^4\ \delta_{Li}\ (mm) - Lithium$$

Comp - 1D Liner Code

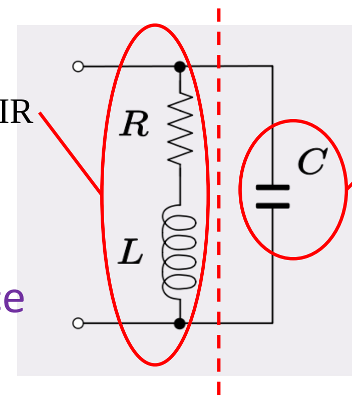
Circuit Parameters

R=3 mΩ
L=20 nH
420 uF
40,000 V

Source Free RLC Circuit

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

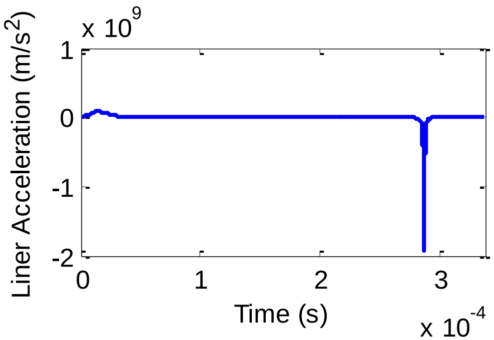
changing inductance

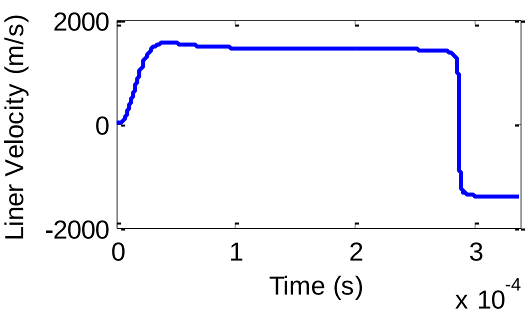


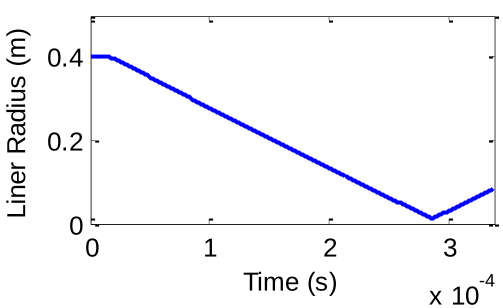
Solved as 2 First Order equations

Liner Parameters

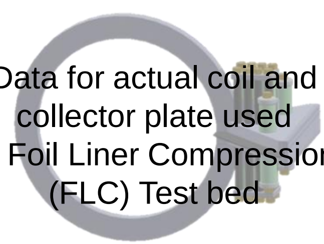
r=0.41 m
w=6 cm
l=0.2 mm



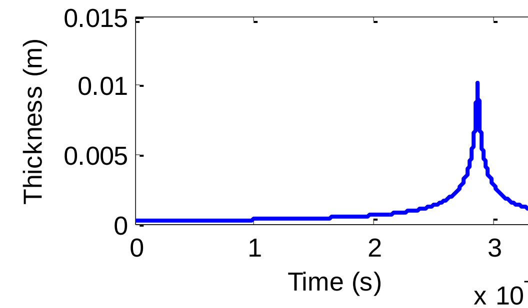


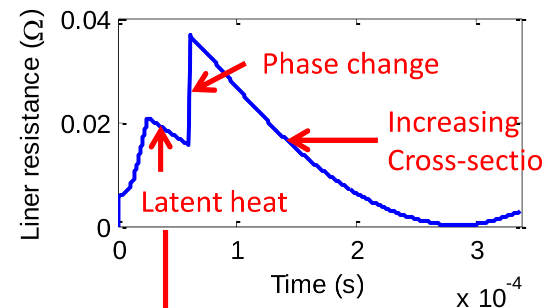


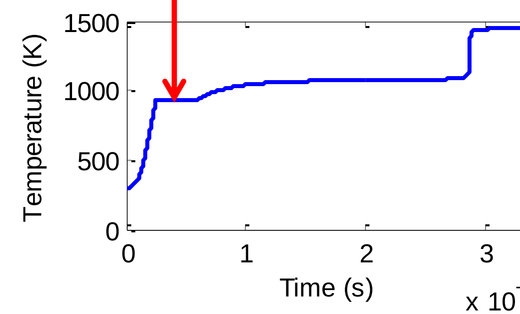
- Various Current waveforms
  - Ringing
  - Crowbar
  - Diode
- Magnetic flux diffusion
- Resistivity - ρ(T)
- Latent heats
- Radiative cooling
- Energy conservation



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

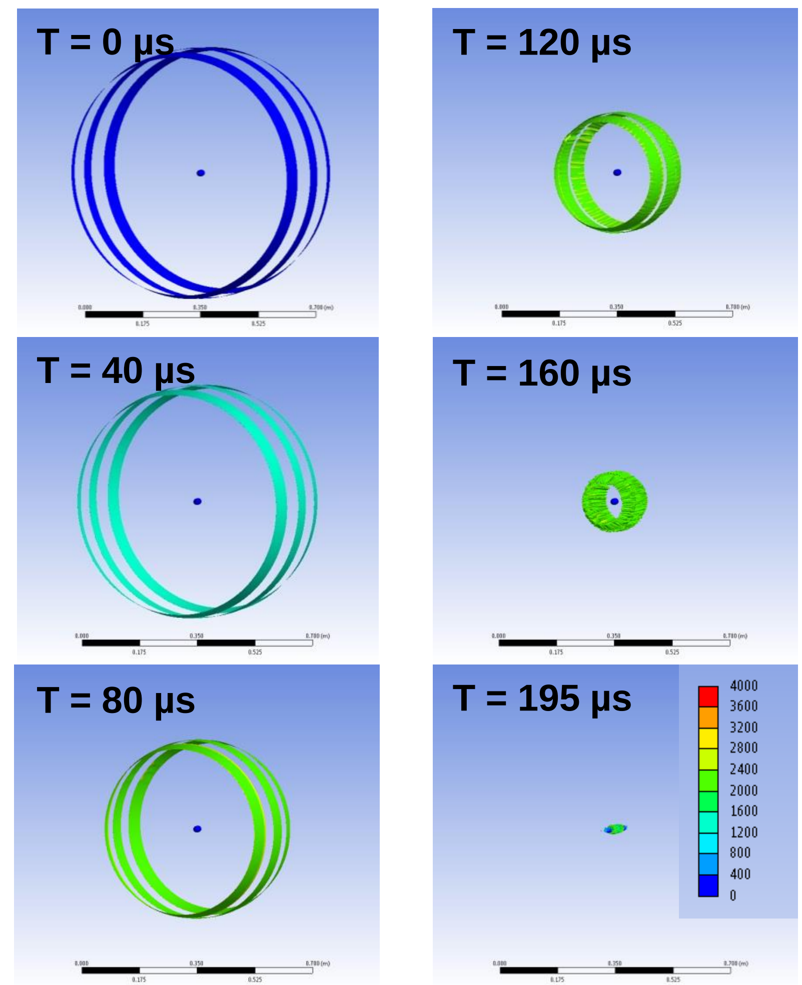






ANSYS Explicit Dynamics® Calculations

- 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