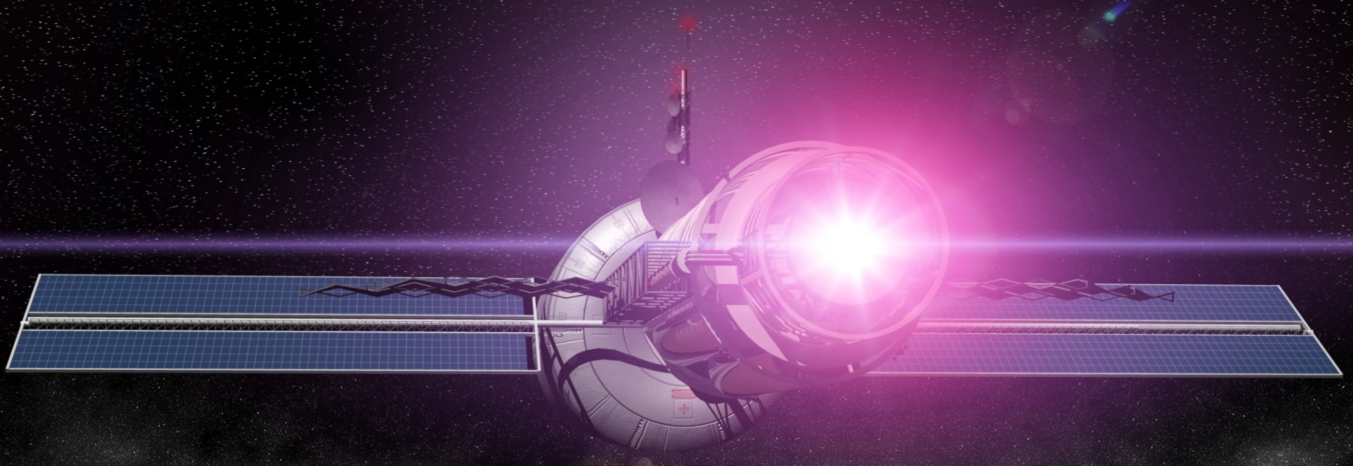
Electromagnetically Driven Fusion Propulsion



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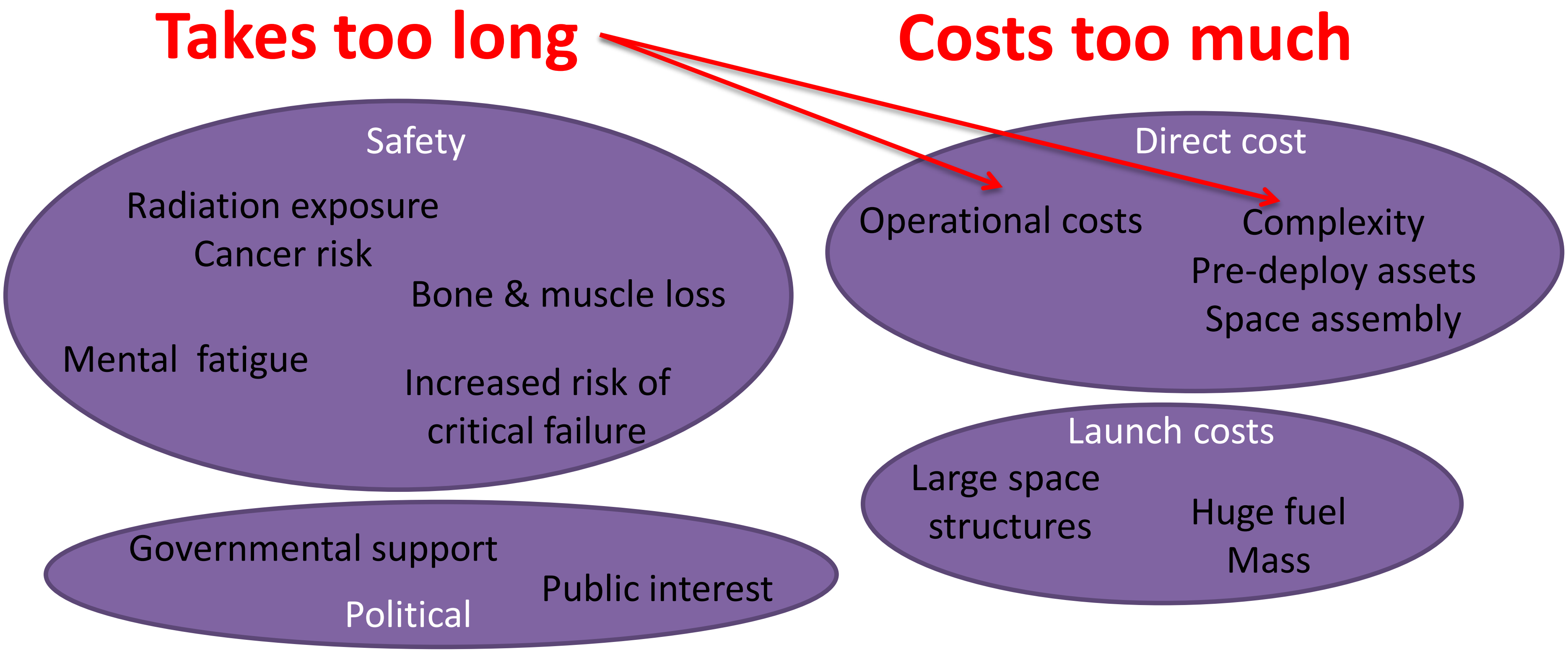
John Slough, David Kirtley, George Votroubek, Christopher Pihl

MSNW LLC, Redmond, WA 98052

IEPC 2013

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

Governmental support

Public interest

Political

Direct cost

Operational costs

Complexity

Pre-deploy assets

Space assembly

Launch costs

Large space structures

Huge fuel

Mass

Solution: **New method of propulsion is needed**

Short trip time

Reduced IMLEO

High $\frac{\textbf{Engine Power}}{\textbf{Spacecraft Mass}}$ **(α)**

High Exit Velocity (I_{sp})

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 **(Short Trip Time)**

(2) adequate time on the surface in which to maximize the return of mission objectives and science

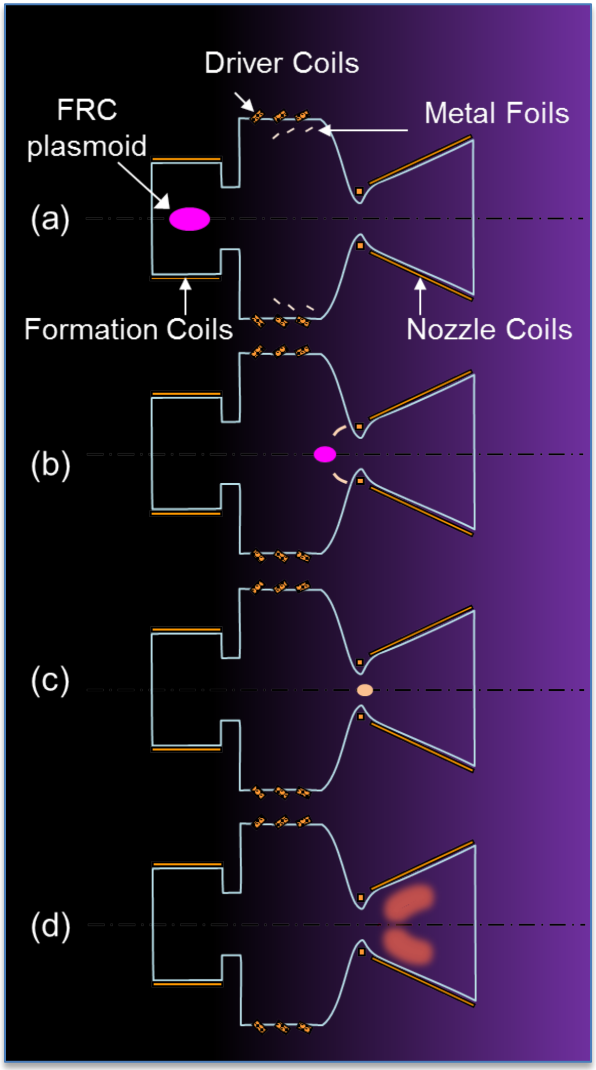
(3) low mission mass, which, in turn, reduces the overall cost and mission complexity **(Reduced IMLEO)**

"ideal mission does not exist"*

Mission down design approach

Mission Architecture Goal
90 Transit times to and from Mars
Adequate stay time (30+ days)
Single launch (130 MT IMLEO)
No pre-deployed assets
DRA 5 Payload mass (63 MT)
Full propulsive MOI & EOI
Reusable spacecraft

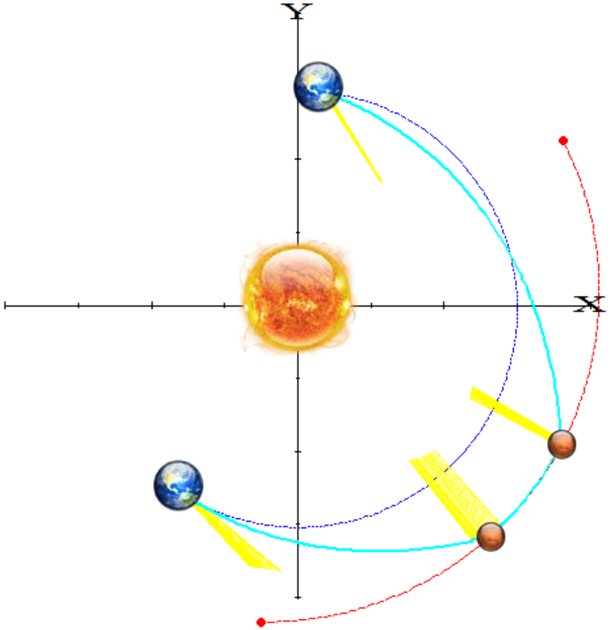
FDR offers the first realistic approach to fusion-based propulsion



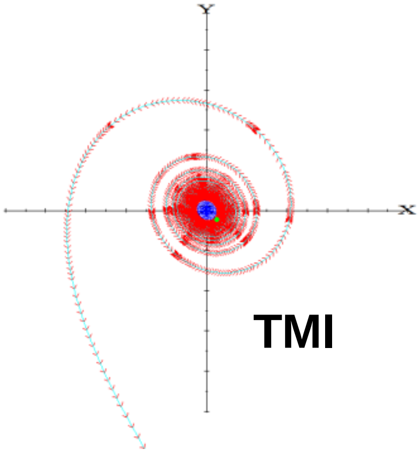
	Benefit	Result
1	Direct transfer of fusion energy to the propellant	High efficiency, low mass engine
2	solid propellant	No significant tankage
3	High exhaust velocities (2000-5000s Isp)	Short trip time, high mass fraction Low IMLEO
4	Magnetic insulated nozzle	No significant physical interaction Minimal 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

210 day Round-trip

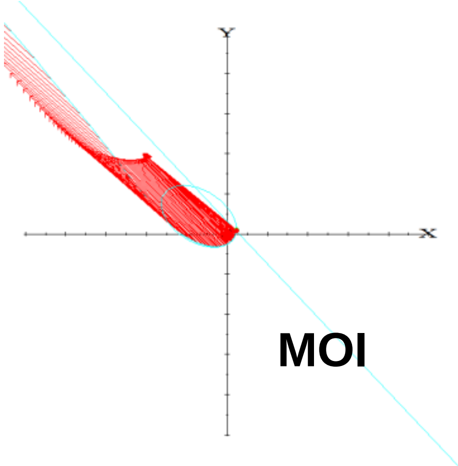
(COPERNICUS)



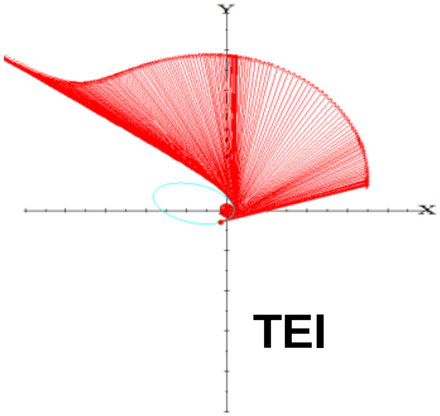
Maneuver	ΔV (km/s)		ΔT (days)	
	Near Body	Simplified	Near Body	Simplified
TMI	12.7	7.3	8.9	7.1
MOI	8.5	13.2	4.7	10.5
TEI	16.6	16.5	1.7	2.9
EOI	11.2	12	1.6	1.6
Total	**49.0**	**49.0**	**16.8**	**22.1**



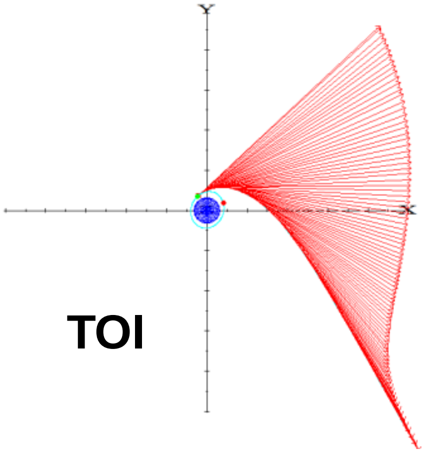
TMI



MOI



TEI



TOI

Spacecraft Scaling

Mission Assumptions		
Payload mass	63	MT
Spacecraft mass	15	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

COPERNICUS

Mission
Architecture
Design

Propulsion Requirements		
Isp	5000	s
Jet Power	36	MW
Specific Power	2.4	kW/kg

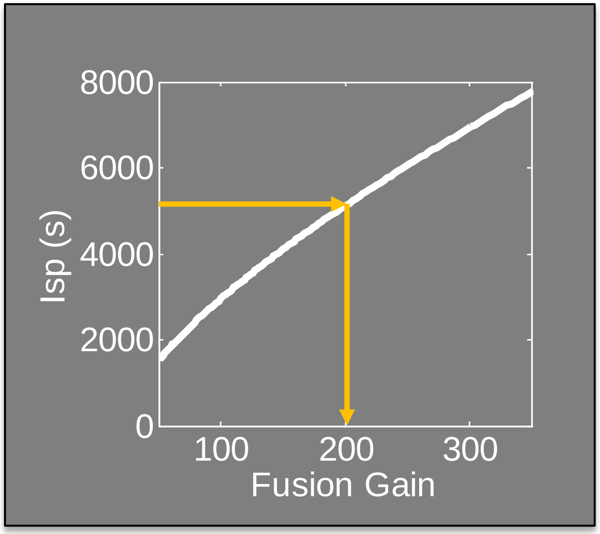
$$E_{out} = G_F E_{in}$$

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

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

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

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



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

2.8 MJ Liner Energy at 45% coupling

6.2 MJ of Capacitors @ 2.5 kJ/kg

2.5 MT of Energy Storage

POWER SOURCE

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

$$\frac{\text{36 MW Jet Power}}{\text{Gain of 200}}$$

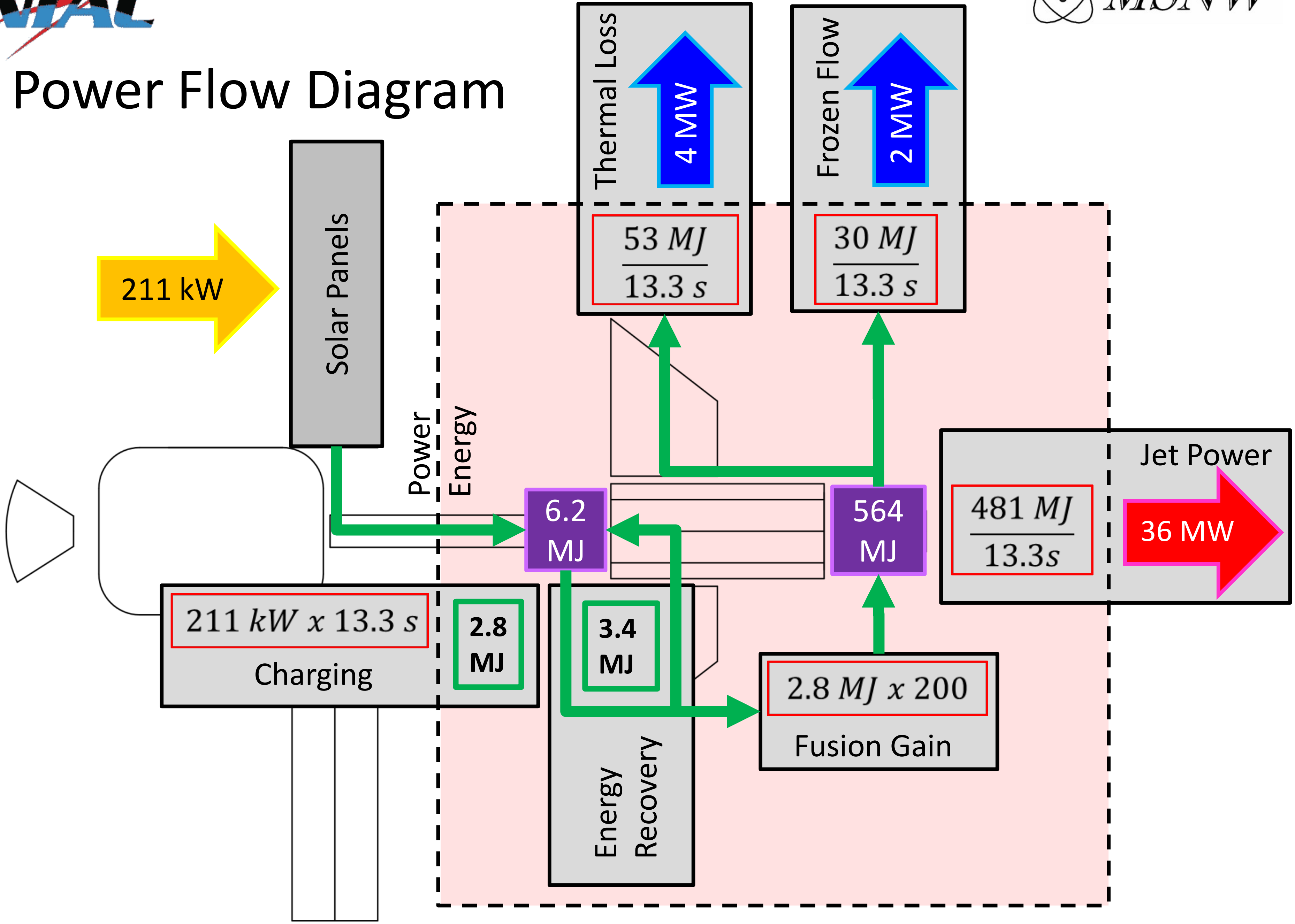
180 kW of Input power OR 400 kW at Mars

200 W/kg

2 MT of Solar Panels

500 W/kg to 1000 W/kg are speculated for the future
Direct energy recovery from fusion reaction possible

Power Flow Diagram



211 kW

Solar Panels

Power

Energy

Thermal Loss

4 MW

$\frac{53\ MJ}{13.3\ s}$

Frozen Flow

2 MW

$\frac{30\ MJ}{13.3\ s}$

6.2 MJ

564 MJ

Jet Power

$\frac{481\ MJ}{13.3 s}$

36 MW

$211\ kW\ x\ 13.3\ s$

Charging

2.8 MJ

3.4 MJ

Energy Recovery

$2.8\ MJ\ x\ 200$

Fusion Gain

Mass Budget

Spacecraft Component	Mass (MT)	TRL	Mission Dependent	Fusion Dependent
Spacecraft structure	3.4	4	X	
Propellant tank	0.1	5	X	X
FRC Formation	0.5	4		X
Propellant Feed	1.2	2		X
Energy storage	2.5	7		X
Liner driver coils	0.3	3		X
Switches and cables	1.2	6		X
Solar Panels	2.0	8	X	X
Thermal Management	1.1	5		X
Nozzle	0.2	2		X
Margin (20%)	2.5			
Spacecraft Mass	**15**		**X**	**X**
Crew habitat	63		X	
Propellant	56		X	X
Total Mass	**134**		**X**	**X**

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 (6.2 MJ @ 2.5 kJ/KG)
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 We, Be, or Cu liners

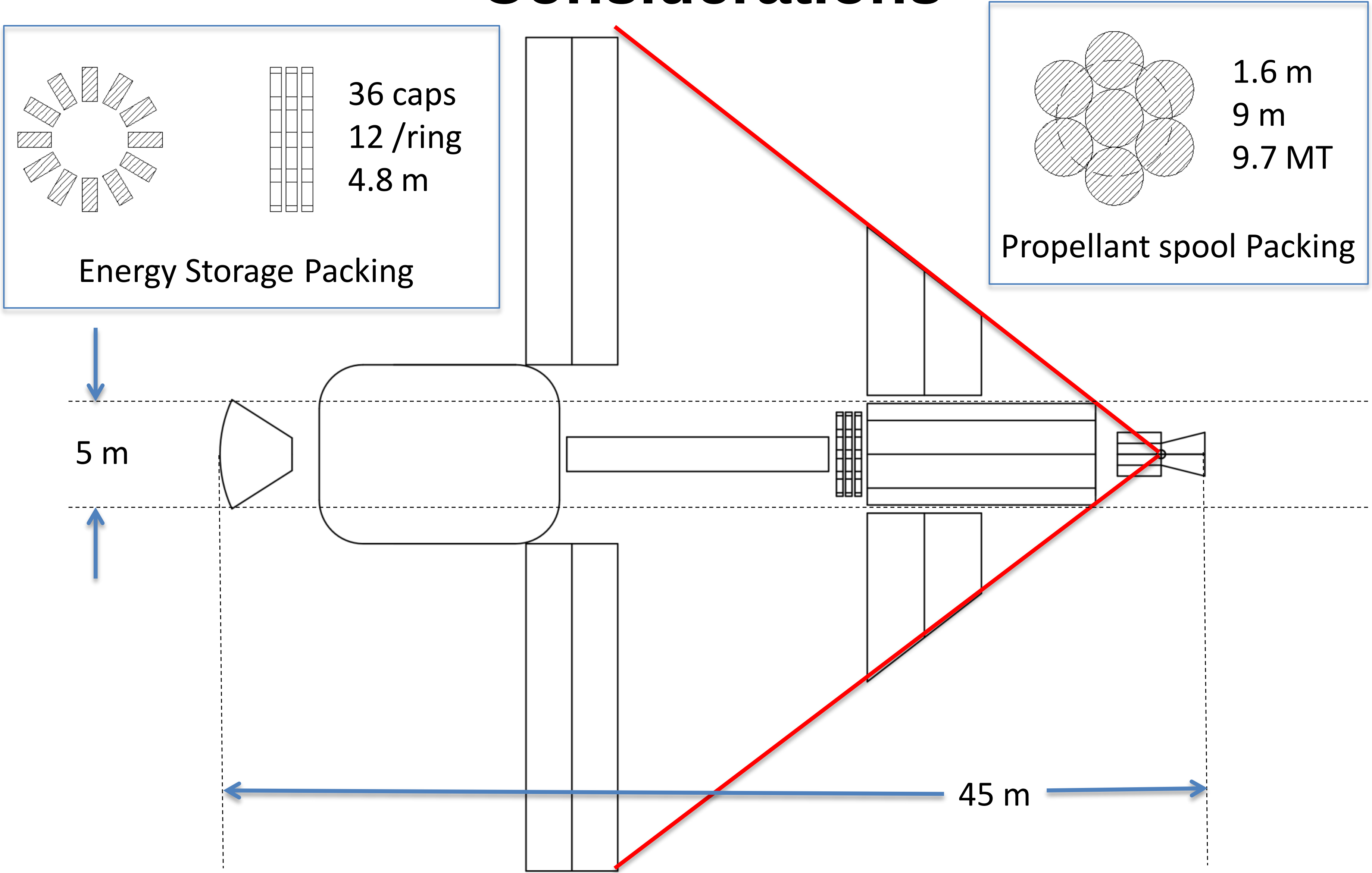
Thermal control, 10% heat rejection @ 1 kW/kg with a margin of 3X

FRC formation based of lab equipment

Propellant Feed – roll of film – ring formation and injection

20% Margin

Spacecraft Layout Considerations



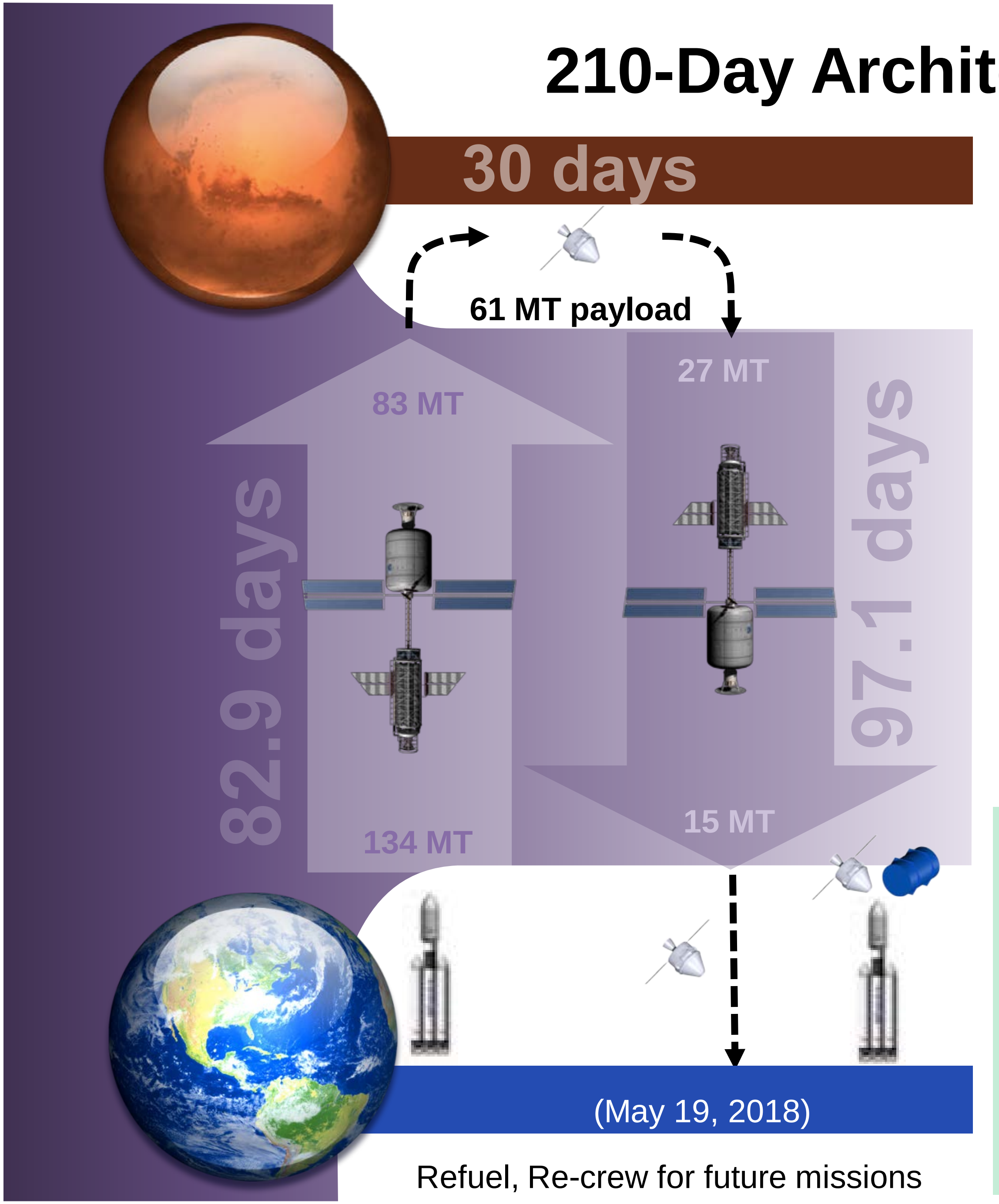
36 caps
12 /ring
4.8 m

Energy Storage Packing

1.6 m
9 m
9.7 MT

Propellant spool Packing

210-Day Architecture Summary



Refuel, Re-crew for future missions

Isp = 5000 s
α = 2.4 kW/kg
Jet power = 36 MW

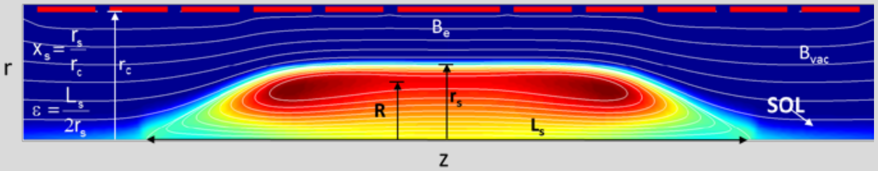
Gain = 200
Spacecraft Mass = 15 MT

FDR
1 launch
134 MT
(IMLEO)
210 days

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

Fusion Approach

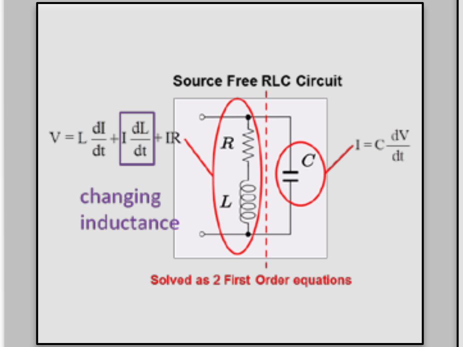
1. Analytical

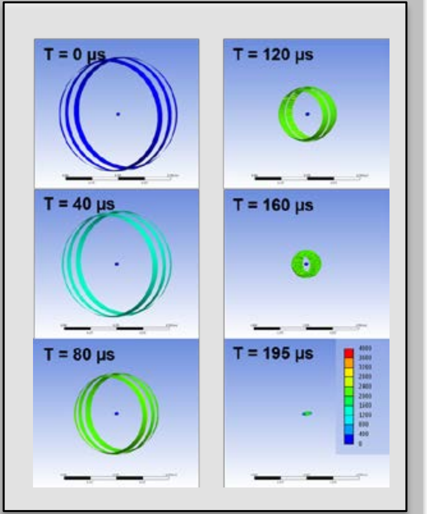


$$E_{fus} \cong 1.2\times10^{-12}\, n_0^2 \langle\sigma v\rangle \frac{4}{3}\pi r_0^3\, \varepsilon\, \tau_D \;=\; 1.1\times10^{-42}\, n_0^2\, T_0^2\, \frac{r_0^4}{v_L}\varepsilon$$

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

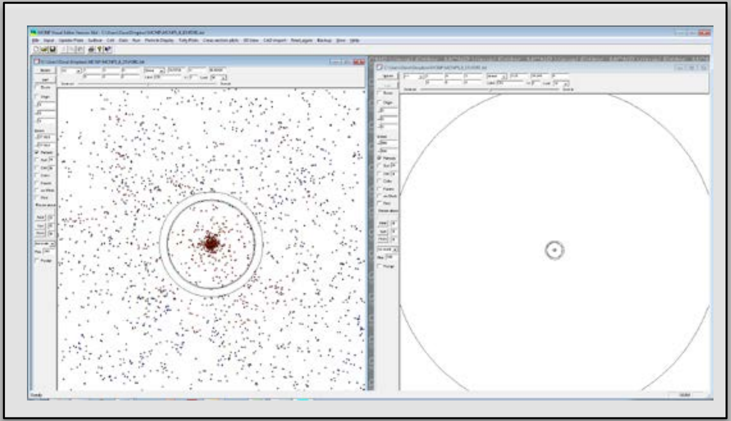
$$G = \frac{E_{fus}}{E_L} \;=\; 1.73\times10^{-3}\sqrt{\frac{M_L}{l_0}}\, B_0 \;=\; 4.3x10^{-8} M_L^{1/2} E_L^{11/8}$$





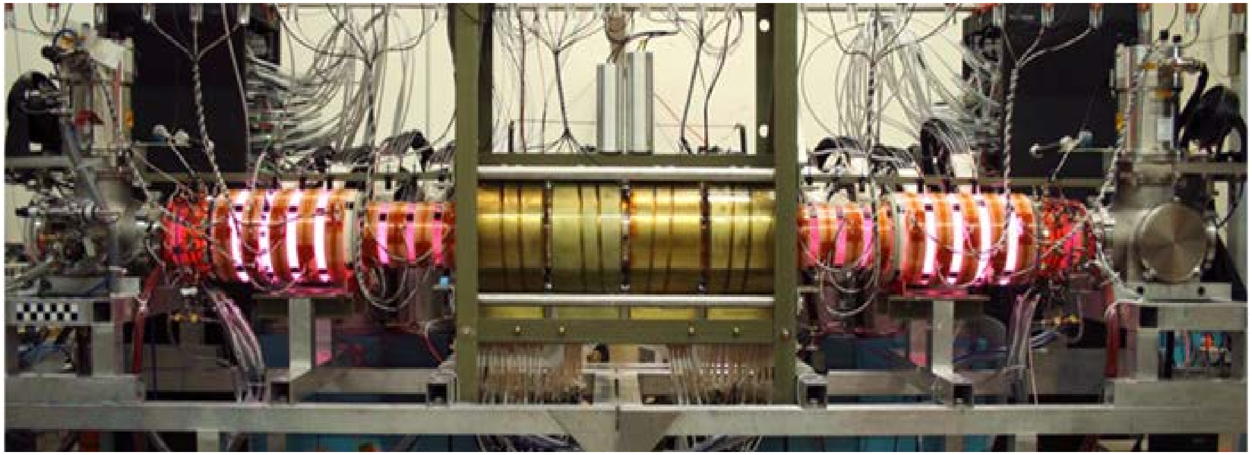
2. Computational

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



3. Experimental Validation

FRC Fusion at MSNW

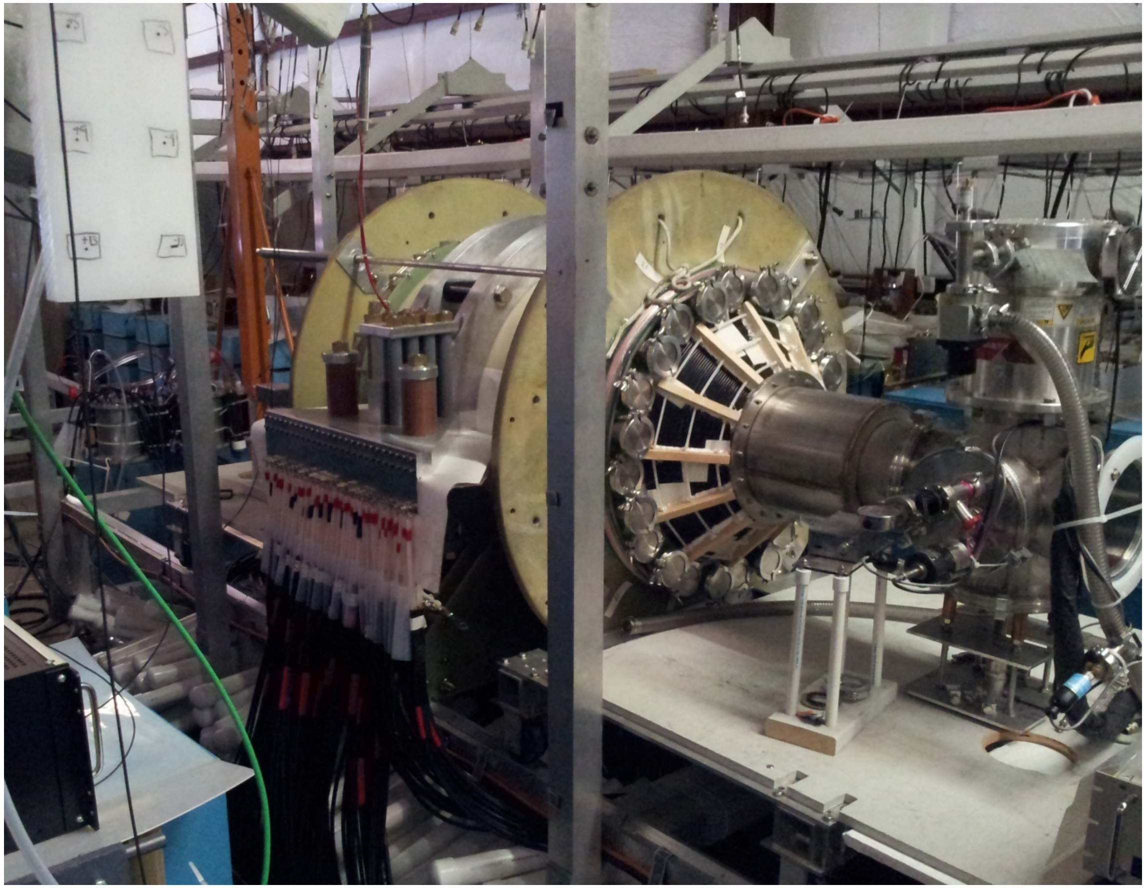


“Creation of a High Temperature Plasma through Merging and Compression of Supersonic Field Reversed Configuration Plasmoids” . Journal of Nuclear Fusion, 2011

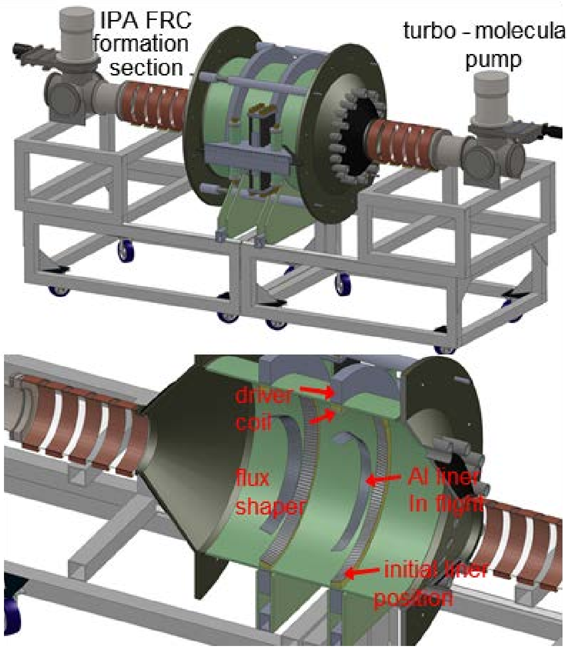
- Fusion with this technique is proven
- $5 M DOE-funded programs demonstrated high field compression of FRC to fusion conditions
  - 2.3 keV Deuterium Ions
  - >100 microsecond lifetimes of 1E22 plasma
  - >1E12 D-D neutrons created in this program
  - At only 1.2 Tesla!
- FRC programs at similar size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

Experimental

IDL Unity Gain Validation Experiment at MSNW

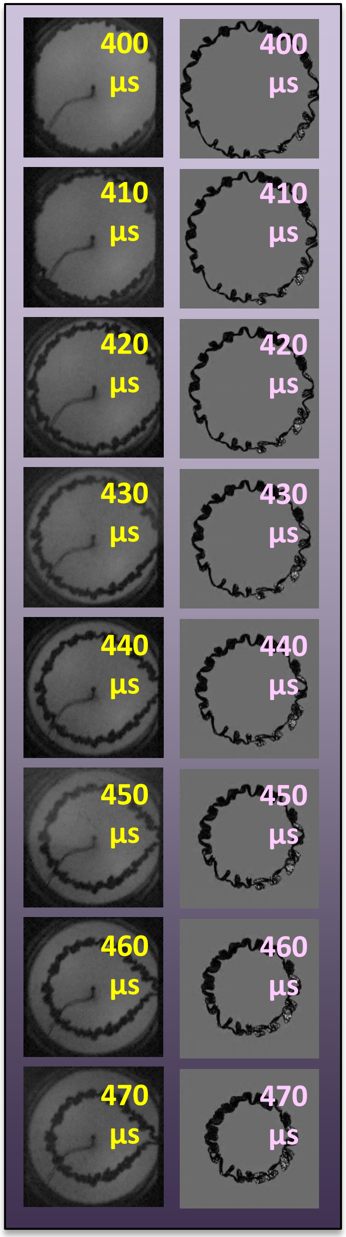


Picture of the FDR validation experiment construction now underway.



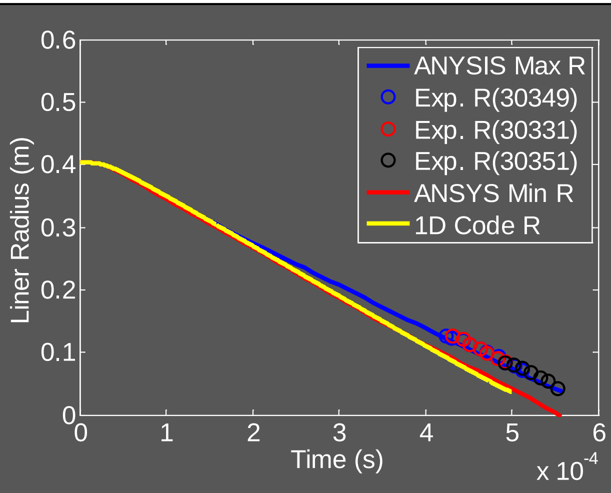
CAD rendering of the Foil Liner Compression (FLC) test facility at MSNW

Experimental Results

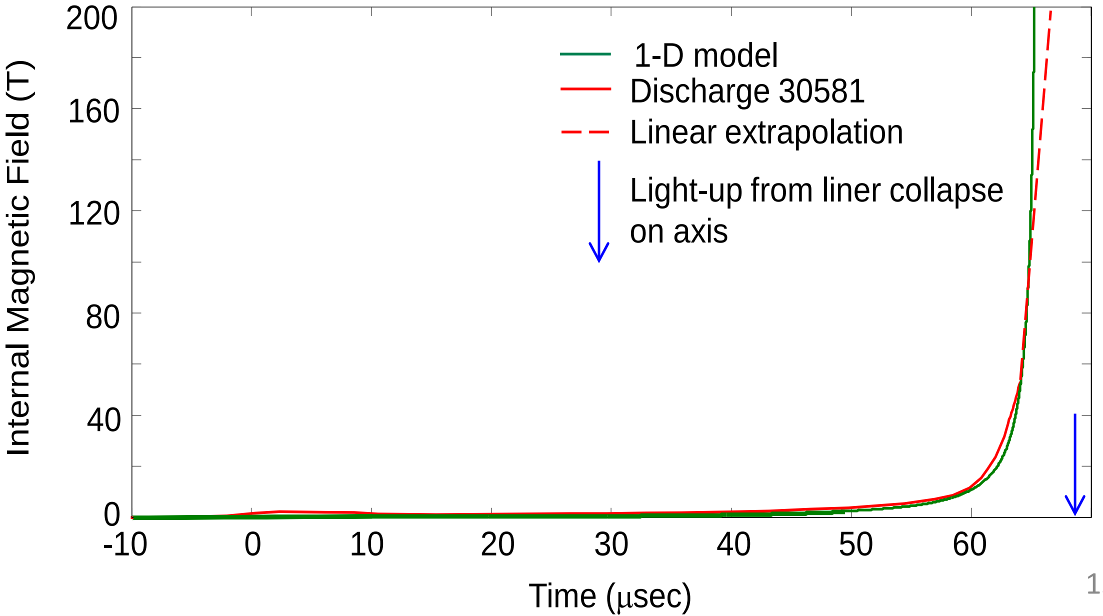


¼ Power Aluminum Liner Testing for code Validation

40 cm
6 cm
0.4mm
20 kV
840 µF

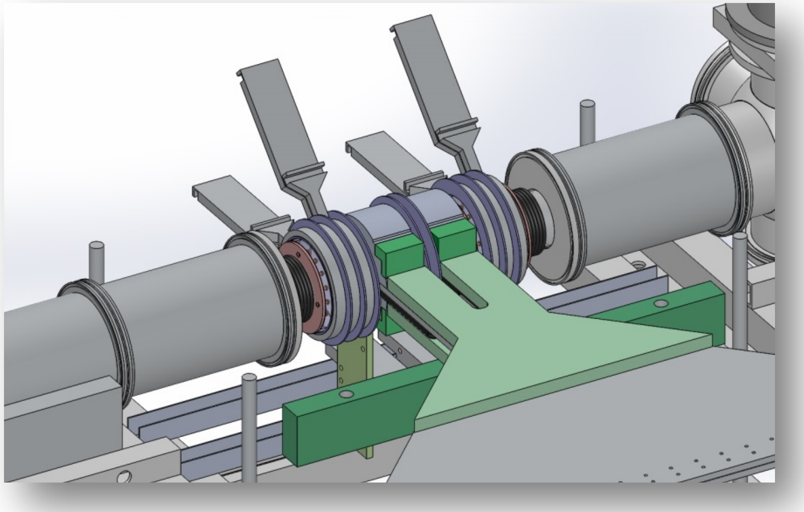


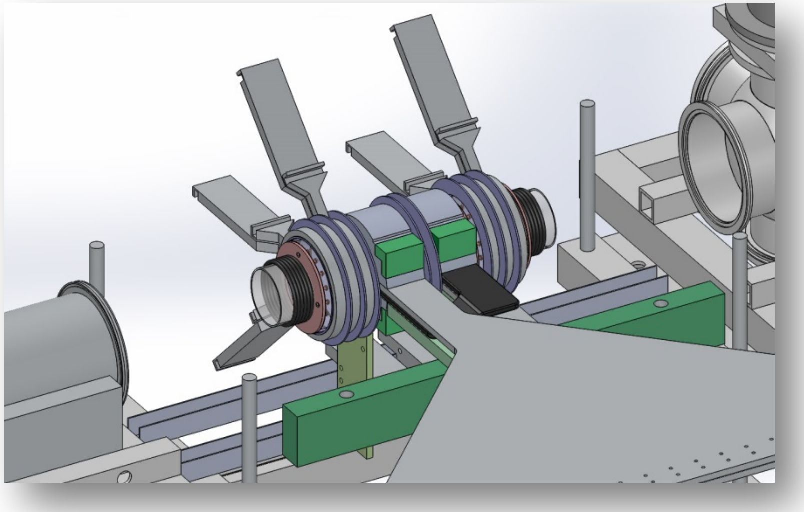
10.3 cm
5 cm
0.4 mm
20 kV
840 µF

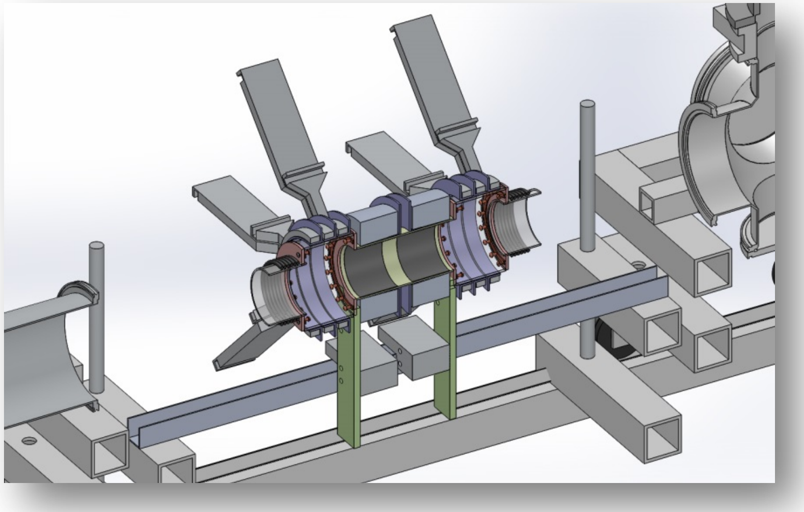


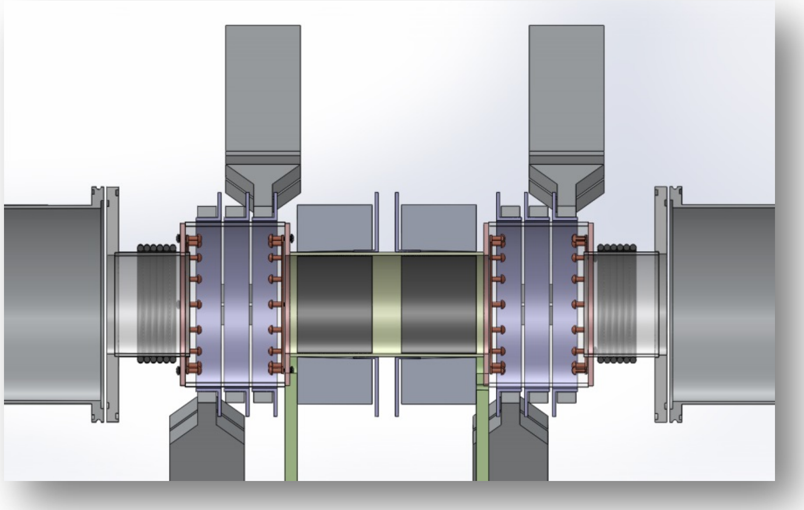
FDR Validation Exp Mk III

5.5 cm, 5 cm, 0.6 mm, 20 kV, 840 μF









Summary

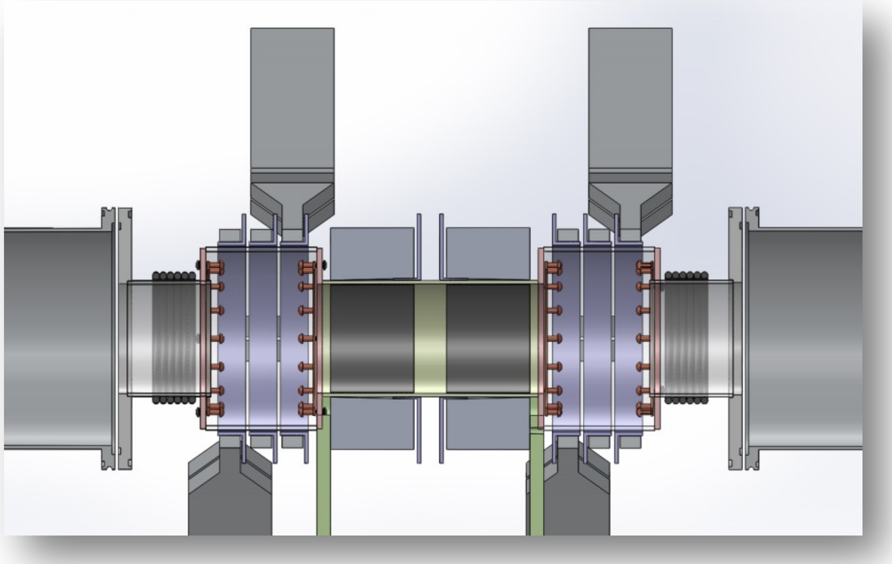
Mission Architecture Goal
90 Transit times to and from Mars
Single launch to Mars (130 MT IMLEO)
No pre-deployed assets
63 MT Payload mass
Full propulsive MOI
Full propulsive EOI
Reusable spacecraft

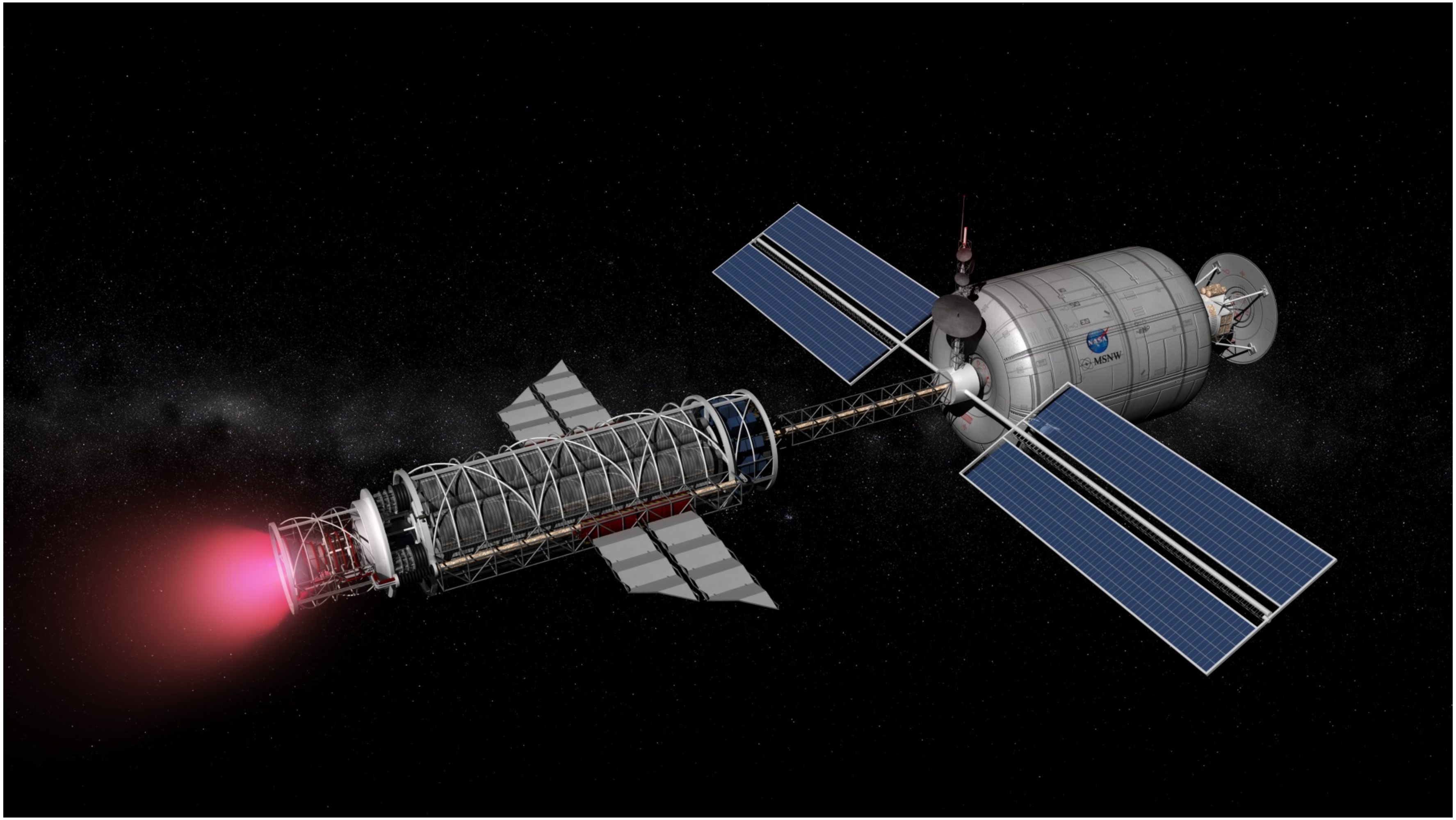
Mission Assumptions		
Payload mass	63	MT
Spacecraft mass	15	MT
IMLEO	130	MT
Earth Orbital Altitude	407	km
Mars park orbit	1	sol
Total Mission Time	210	days
Stay Time	30	days

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

Halfway through Phase 2 NIAC

- Mission Architecture
- Spacecraft Design
- Fusion Physics
  - Analytical
  - Computational
  - Experimental
    - 60 T measured
    - corresponds to 100-200 T





The Fusion Driven Rocket is being developed by MSNW and The University of Washington

With Support from NASA’s Innovative Advanced Concepts

BACK-UP SLIDES

Anticipated Parameters from FDR Validation Experiment

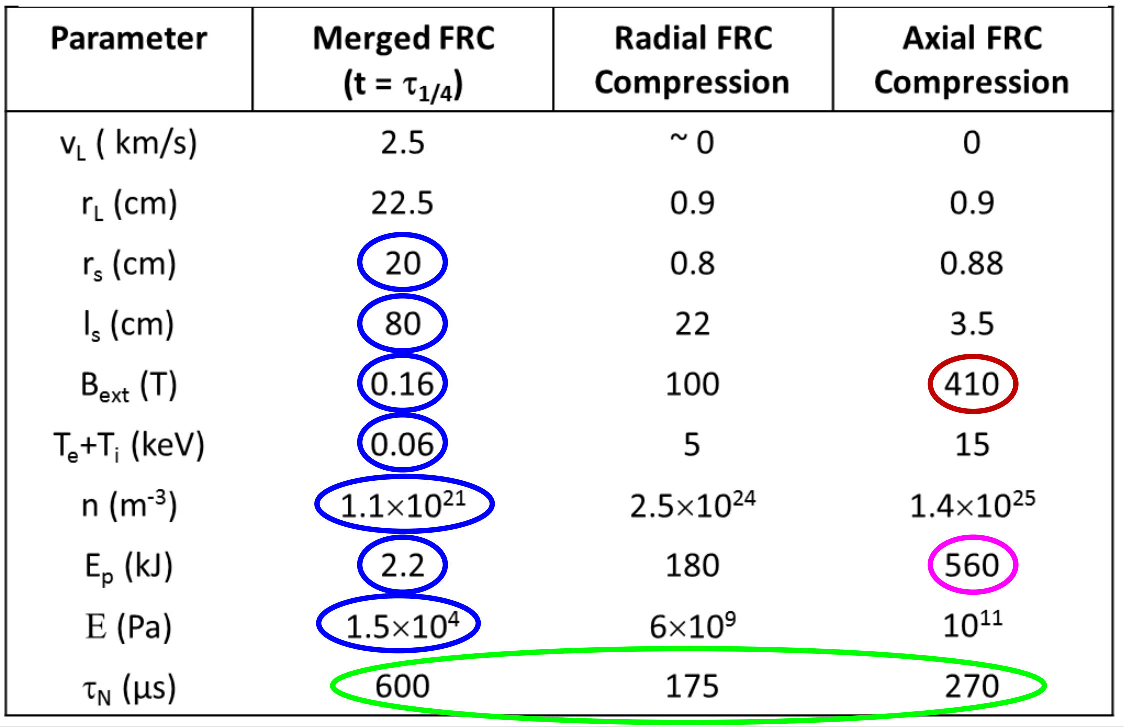
FRC adiabatic scaling laws

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

$\Rightarrow$

$T \sim B_e^{4/5}$
$n \sim B_e^{6/5}$
$r_s^2 l_s \sim B_e^{-6/5}$
$l_s \sim r_s^{2/5}$

In experiment, FRC radial and axial compressions would occur simultaneously



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 same as past FRC's

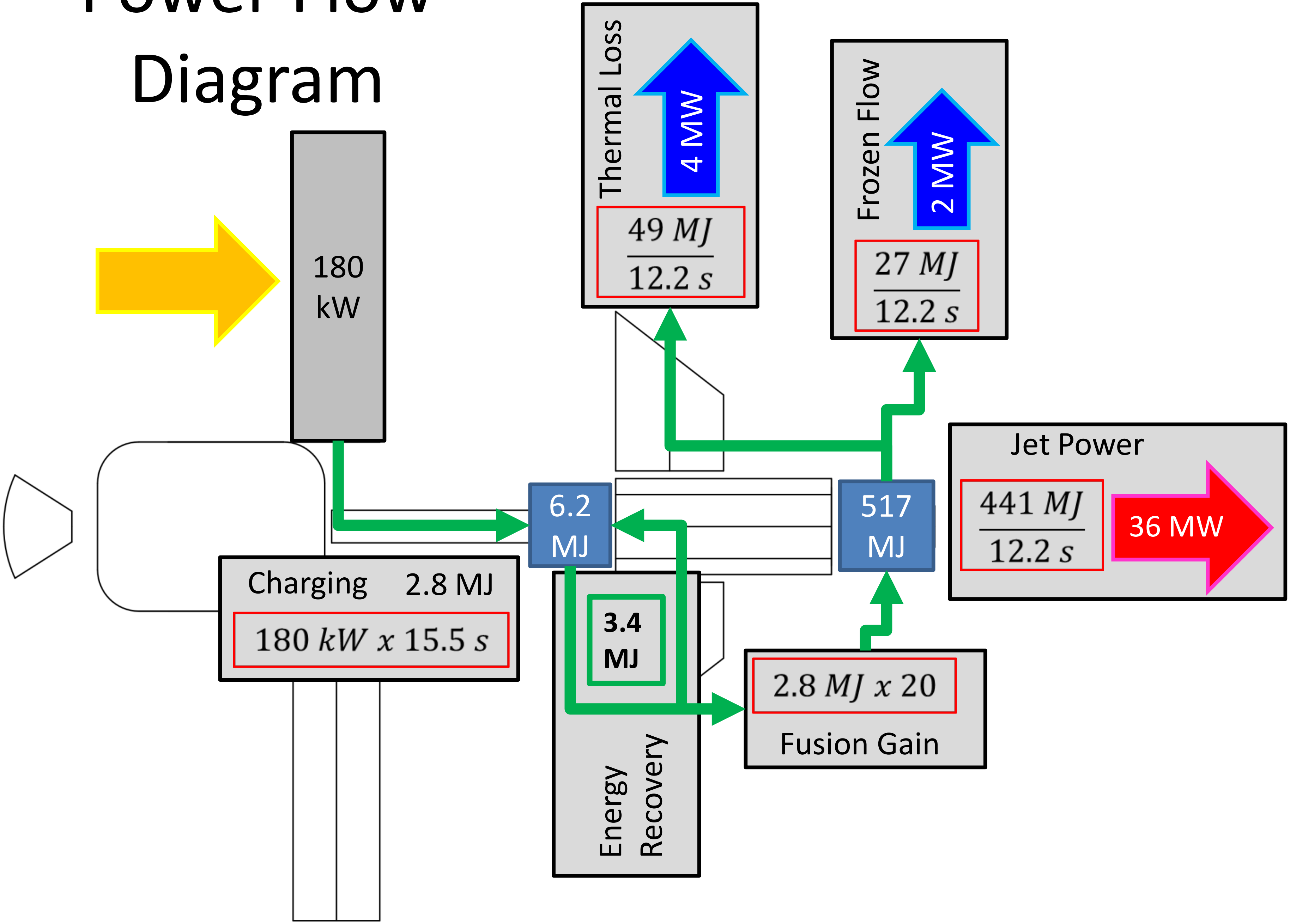
Final field similar to that achieved in several flux compression expts.

Sub MJ FRC Requires only 33% bank eff.

FRC lifetime
>> τ_{dwell} ~ 4 μs

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

Power Flow Diagram



180 kW

Thermal Loss

4 MW

$\frac{49\ MJ}{12.2\ s}$

Frozen Flow

2 MW

$\frac{27\ MJ}{12.2\ s}$

Jet Power

$\frac{441\ MJ}{12.2\ s}$

36 MW

6.2 MJ

517 MJ

Charging 2.8 MJ

$180\ kW\ x\ 15.5\ s$

3.4 MJ

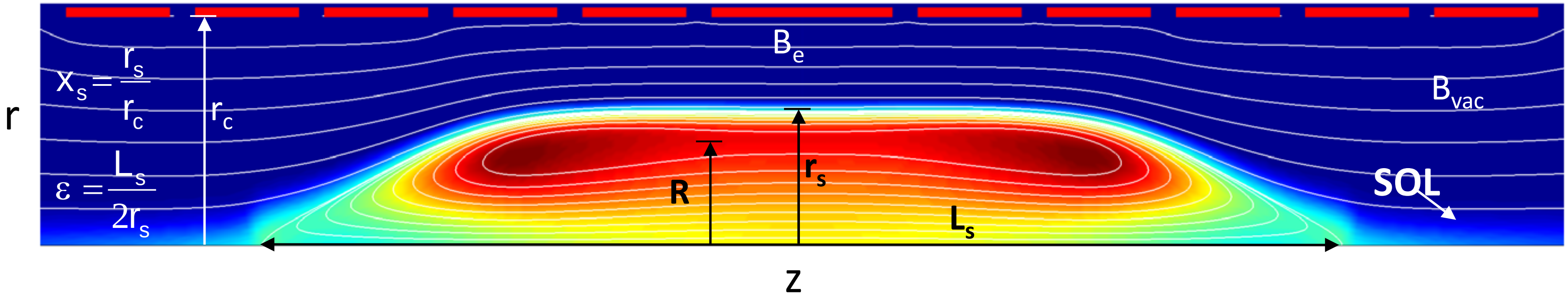
Energy Recovery

$2.8\ MJ\ x\ 20$

Fusion Gain

Field Reversed Configuration (FRC)

Magnetic Field lines and Pressure Contours



Key Equilibrium Relations:

$$\left\{ \begin{array}{l} B_{ext} = \dfrac{B_{vac}}{1 - x_s^2} \\[2em] P_0 = n_0 kT = \dfrac{B_{ext}^2}{2\mu_0} \\[2em] \langle \beta \rangle = 1 - \dfrac{1}{2} x_s^2 \end{array} \right.$$

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:

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

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:

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

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:

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

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 $\Rightarrow$

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

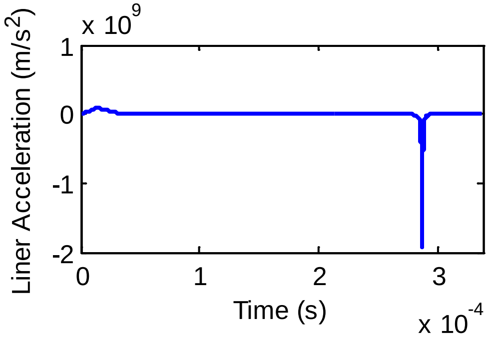
to express G in terms of the liner kinetic energy E_L and mass M_L only.

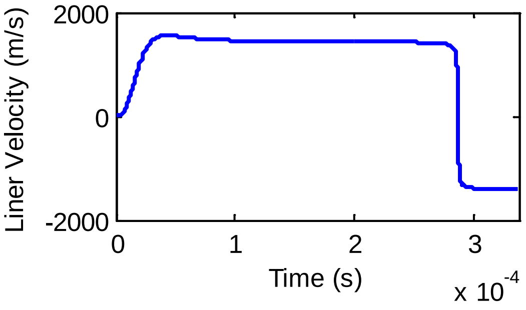
Fusion Ignition will amplify gain by large factor. It is estimated that the total fusion gain $G_F \sim 5\text{-}10 \cdot G$. For a large margin of safety, it is assumed that:
$G_F = 2.5G$ or,

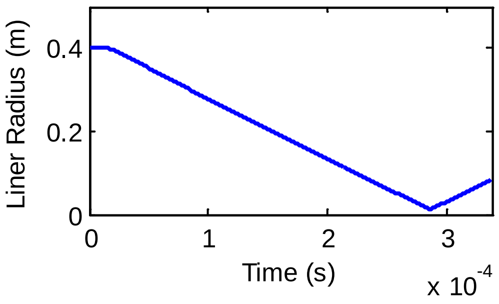
$$\boldsymbol{G_F = 1.1\times10^{-7}\, M_L^{1/2}\, E_L^{11/8}}$$

Comp - 1D Liner Code

Circuit Parameters
R=3 mΩ
L=20 nH
420 uF
40,000 V

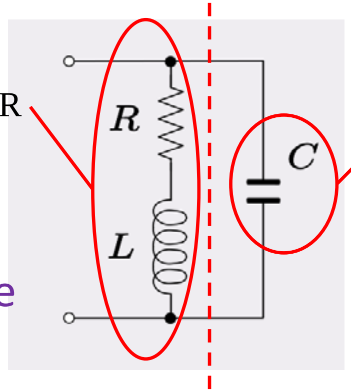






Source Free RLC Circuit

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



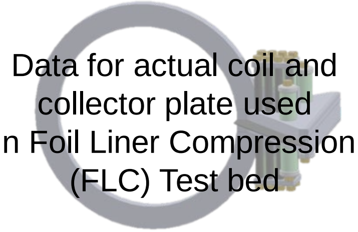
$$I = C\frac{dV}{dt}$$

changing inductance

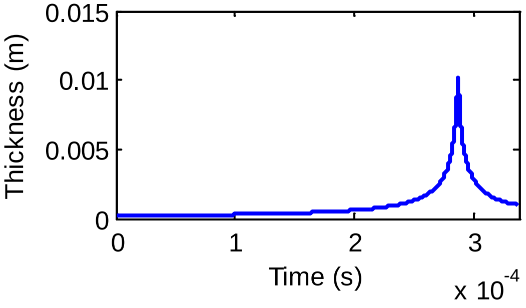
Solved as 2 First Order equations

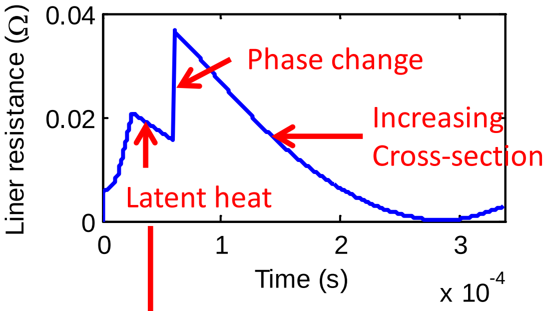
Liner Parameters
r=0.41 m
w=6 cm
l=0.2 mm

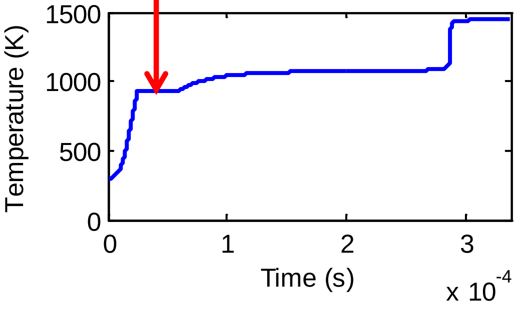
- Various Current waveforms
  - Ringing
  - Crowbar
  - Diode
- Magnetic flux diffusion
- Resistivity - ρ(T)
- Latent heats
- Radiative cooling
- Energy conservation



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

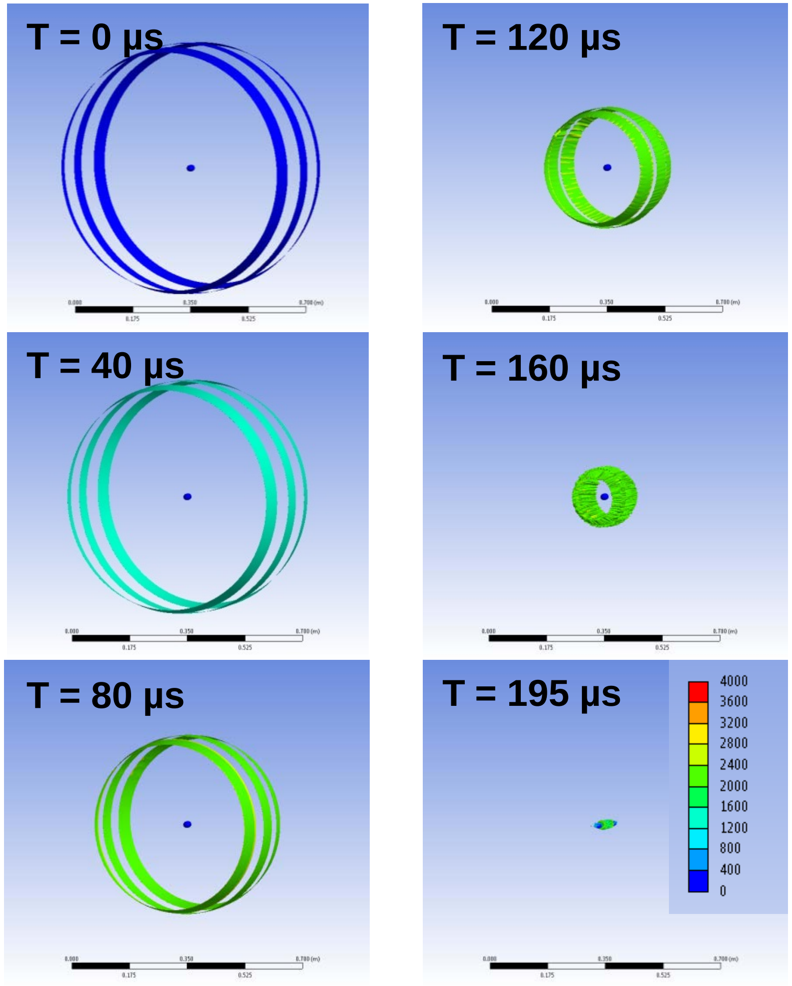






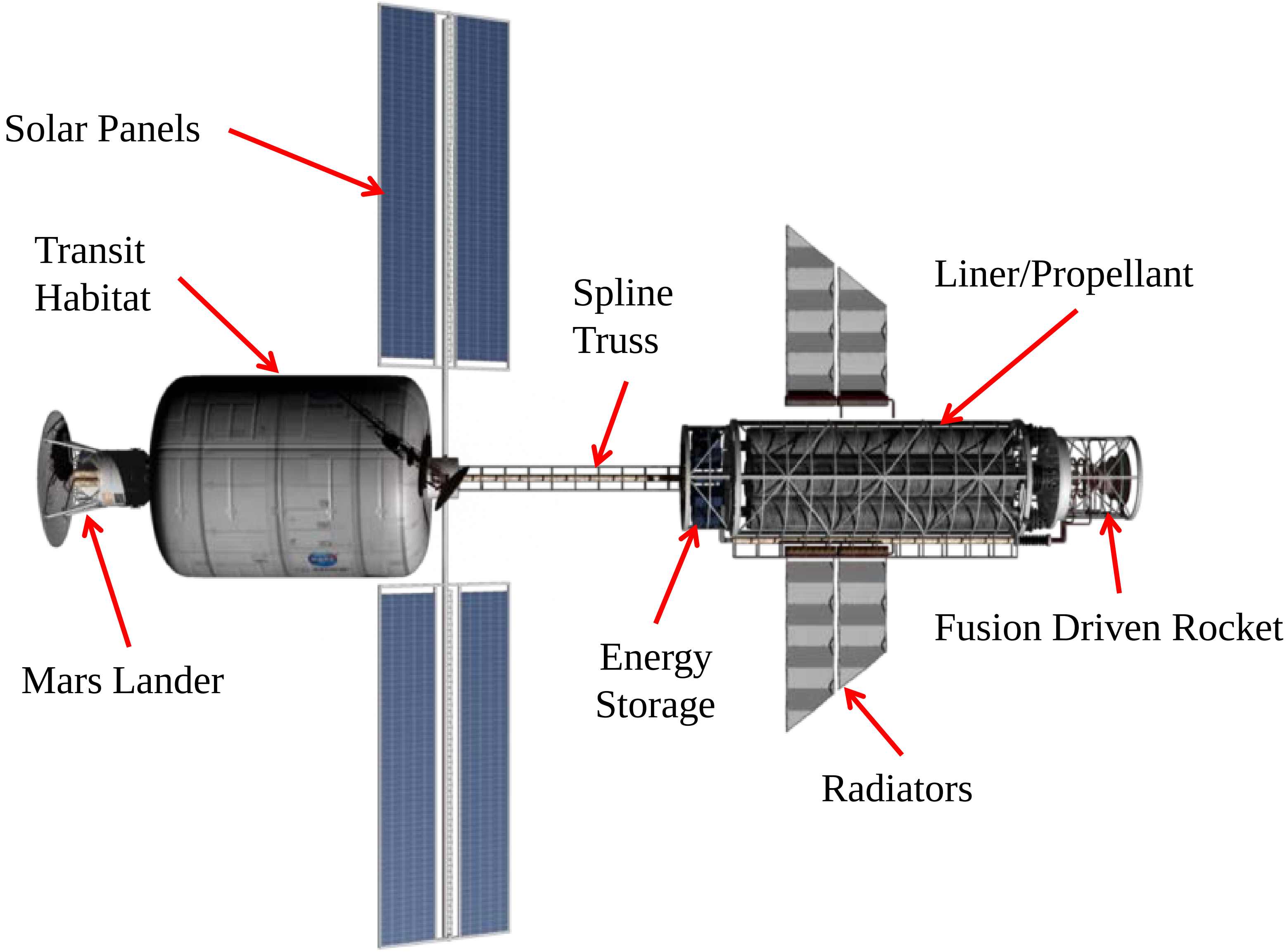
ANSYS Explicit Dynamics® Calculations

- 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

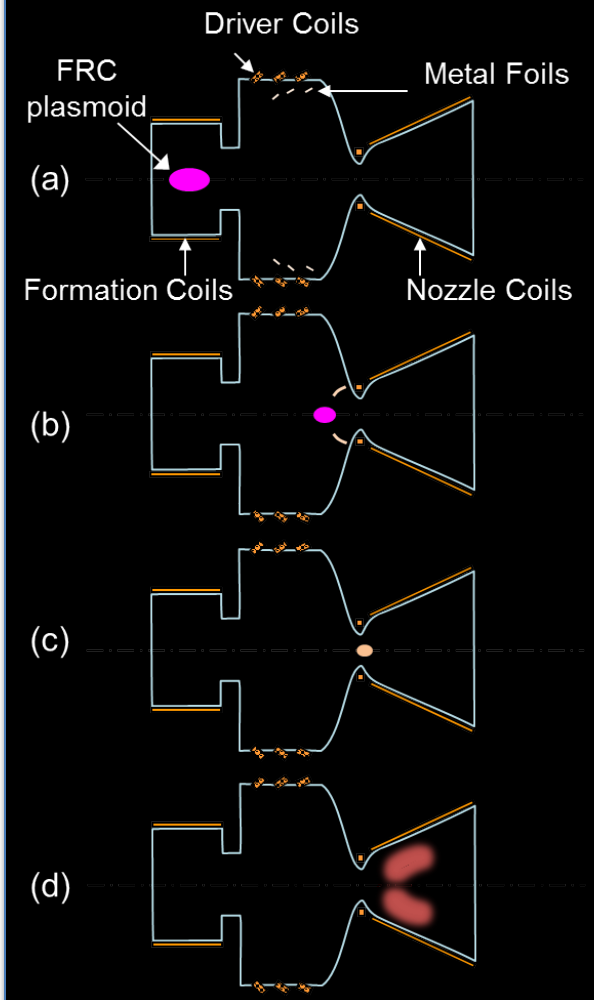


Liner behavior agreed very well with 1D Liner Code

FDR Spacecraft Layout



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

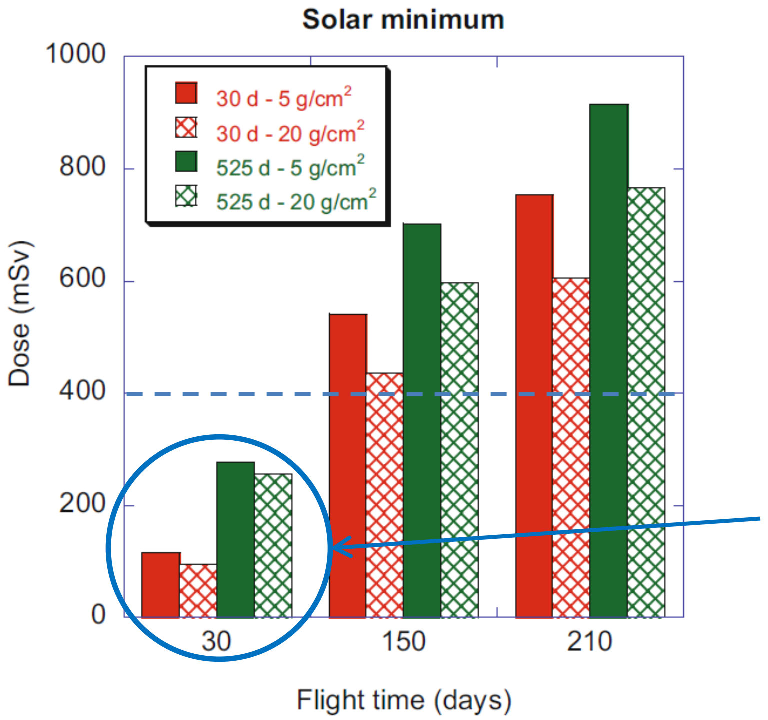
(d) Vaporized and ionized by fusion neutrons and alphas, the plasma blanket expands against the divergent magnetic field resulting directed flow of the metal plasma out of the magnetic nozzle.

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

Estimated Total Equivalent Doses

🟥 Mars sortie mission (30 days stay)

🟩 Long stay at Mars base (525 days)



Current technology (210 days)

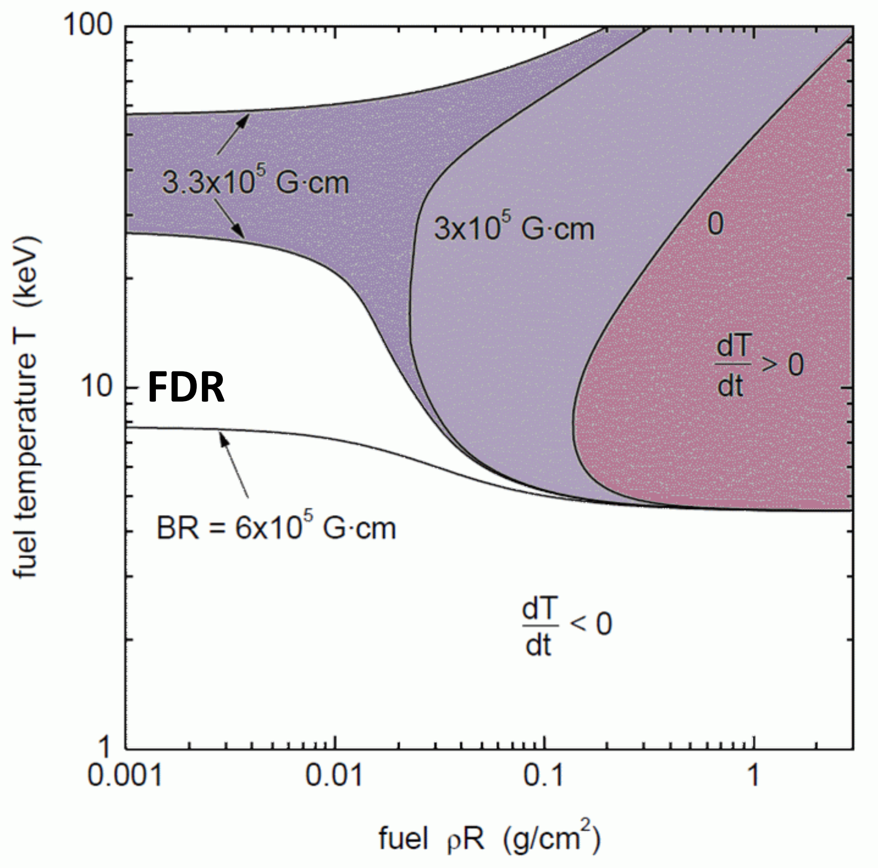
NTP/NEP (150 days)

Fusion Driven Rocket (30 days)

Solid bars – calculation for spacecraft with a minimum shield (5 g/cm^2 Al)
Dashed bars – calculations for a thick shield (20 g/cm^2 Al)

- The career limit is 400 mSv for a 25 year old for a 3% risk of fatal cancer
- There is still great uncertainty as to what the actual risk is for long term low level exposure

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.

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.

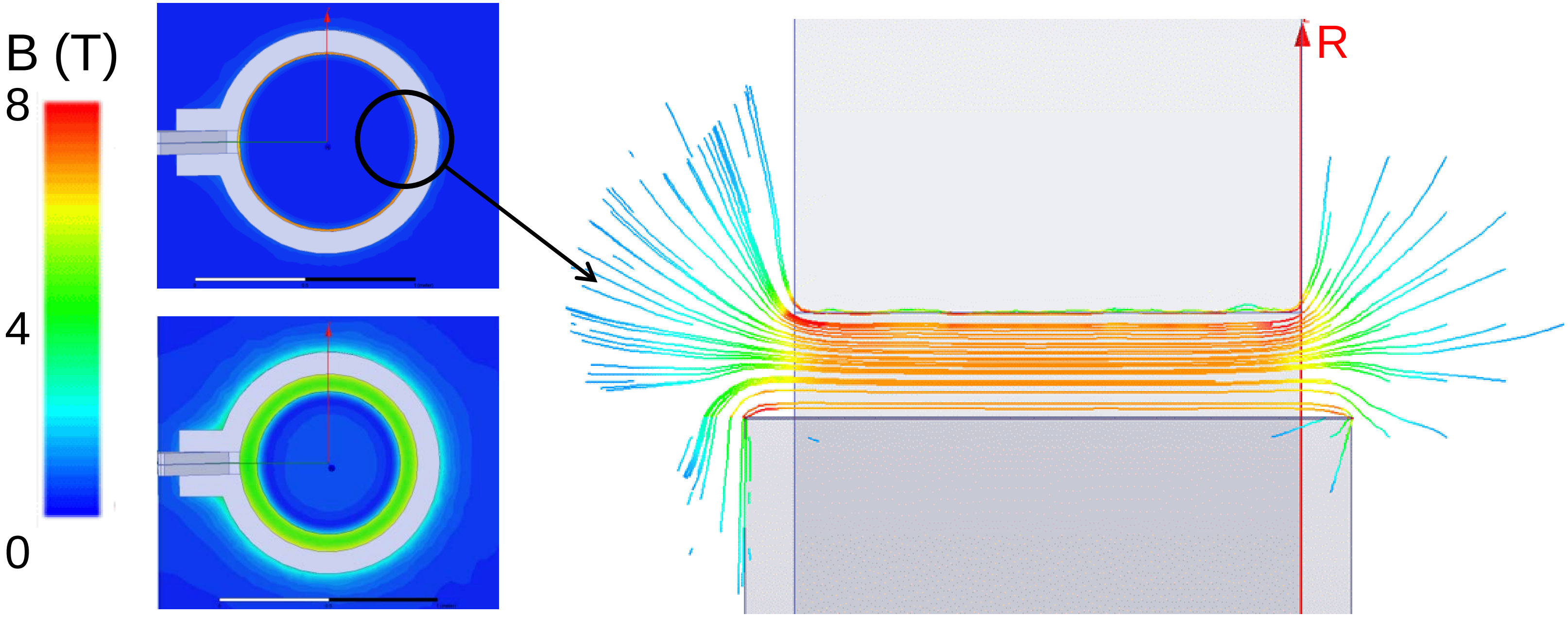
- The driving force is simply the magnetic pressure ($B^2/2\mu_0$) applied over the surface area of the metal facing the coil when in close proximity to the driving coil.
- The current can be related to the force through Ampere’s law which can be reasonably approximated as $B = \mu_0 I/w$.

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

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

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

ANSYS Maxwell® Calculations of the 3D Electromagnetic Fields



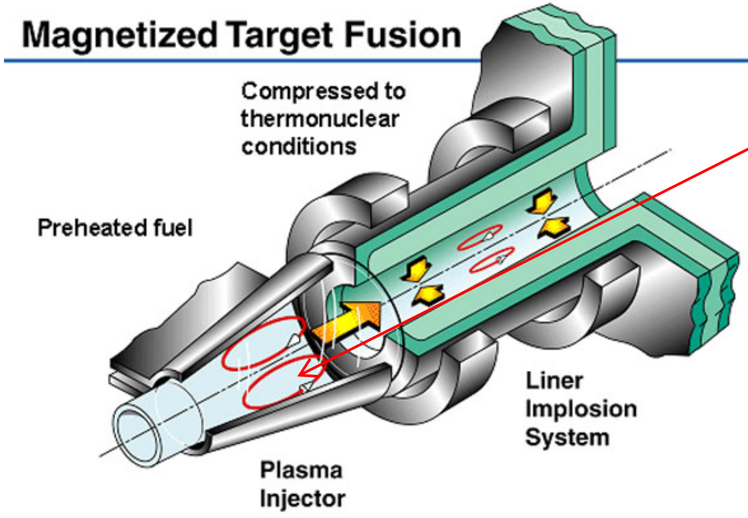
- Solution for a 0.4 m radius coil driving a 6 cm wide, 0.2 mm thick Al liner.
- The circuit was based on the capacitor bank currently available at the UW Plasma Dynamics Laboratory.
- The spatial forces on the liner at various times and radii are calculated and used as input into the dynamic calculation similar to the one shown above.
- Mutual interaction between coils and liners will also be investigated.

Magneto-Inertial Fusion
Two Approaches

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

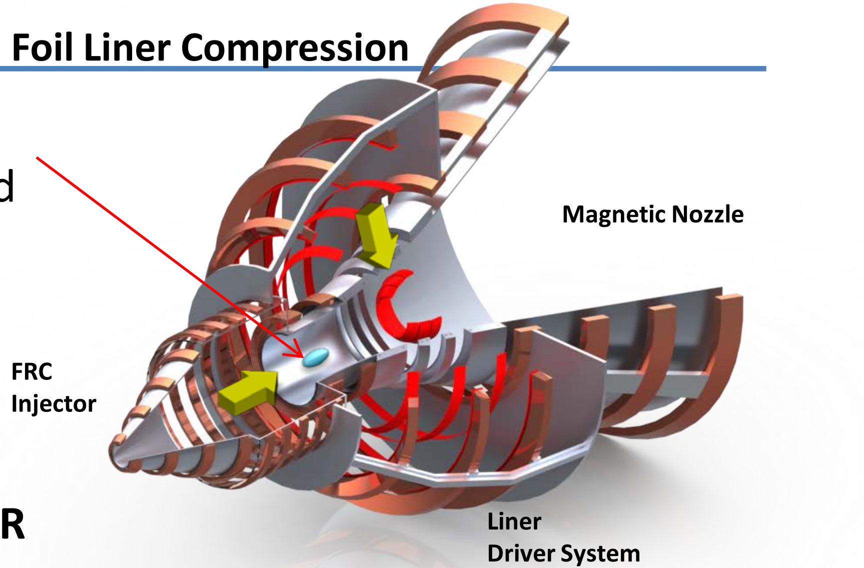
Liner implosion from j x B force between external coil and induced liner currents

Magnetized Target Fusion



FRC
plasmoid

Foil Liner Compression



MTF
Issues:

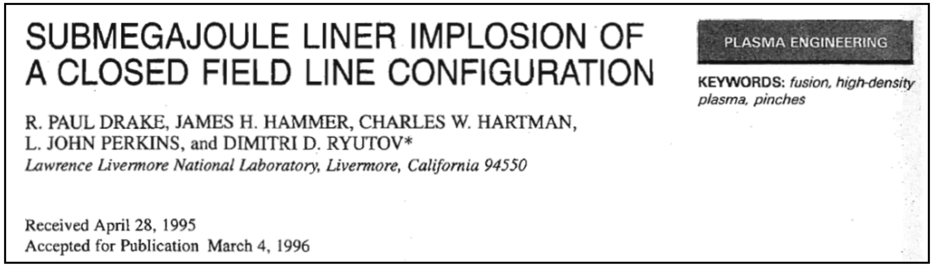
- Extremely low inductance load difficult to drive (massively parallel HV caps and switches)
- Close proximity and electrical contact ⇒ major collateral damage with each pulse
- Small FRC must be formed close to implosion ⇒ marginal B for ignition w injector destruction
- Only inefficient 2D compression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

Theoretical Validation of Key FDR Elements (peer reviewed papers)



SUBMEGAJOULE LINER IMPLOSION OF A CLOSED FIELD LINE CONFIGURATION

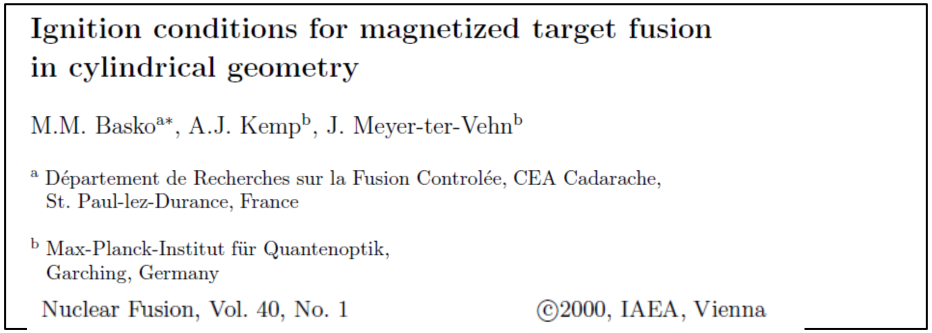
PLASMA ENGINEERING

KEYWORDS: *fusion, high-density plasma, pinches*

R. PAUL DRAKE, JAMES H. HAMMER, CHARLES W. HARTMAN, L. JOHN PERKINS, and DIMITRI D. RYUTOV*
Lawrence Livermore National Laboratory, Livermore, California 94550

Received April 28, 1995
Accepted for Publication March 4, 1996

- Importance of 3D compression
- Superiority of high β FRC target
- Magnetic field limits thermal and particle loss - **even with (cold) wall confinement and β > 1**



Ignition conditions for magnetized target fusion in cylindrical geometry

M.M. Basko[a]*, A.J. Kemp[b], J. Meyer-ter-Vehn[b]

[a] Département de Recherches sur la Fusion Controlée, CEA Cadarache, St. Paul-lez-Durance, France

[b] Max-Planck-Institut für Quantenoptik, Garching, Germany

Nuclear Fusion, Vol. 40, No. 1 ©2000, IAEA, Vienna

- Ignition possible with magnetized plasma **where ρR <<1** but BR > 60 T-cm.
- Magnetic field well within range of larger FRCs.

Fusion Based on the Inductively-Driven Lithium Liner Compression of an FRC Plasmoid

John Slough, David Kirtley, Anthony Pancotti, Christopher Pihl, George Votroubek
(Submitted to *Journal of Fusion Energy* 2012)

- Method for producing 3D liner implosions with stand-off
- Generation of FRC plasma target with sufficient magnetization and confinement for ignition
- Method for efficient conversion of plasma, radiation, and fusion energy in a manner that protects and magnetically isolates reactor

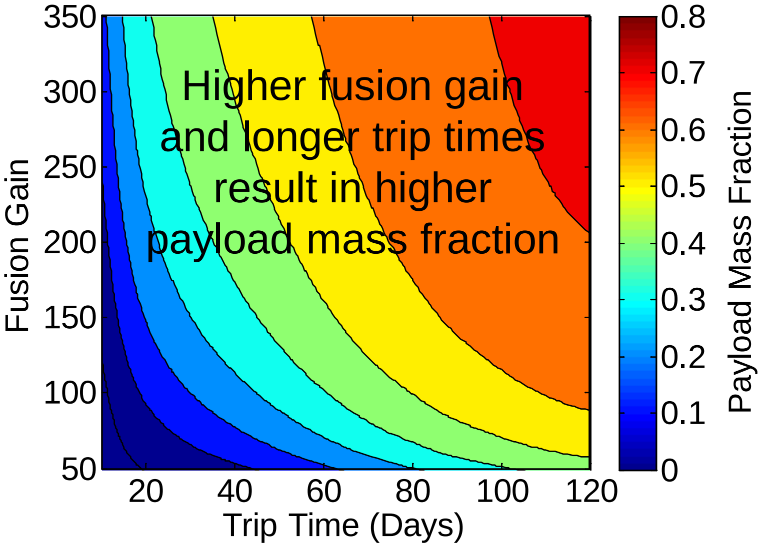
Initial Mission Studies

Fusion Assumptions:

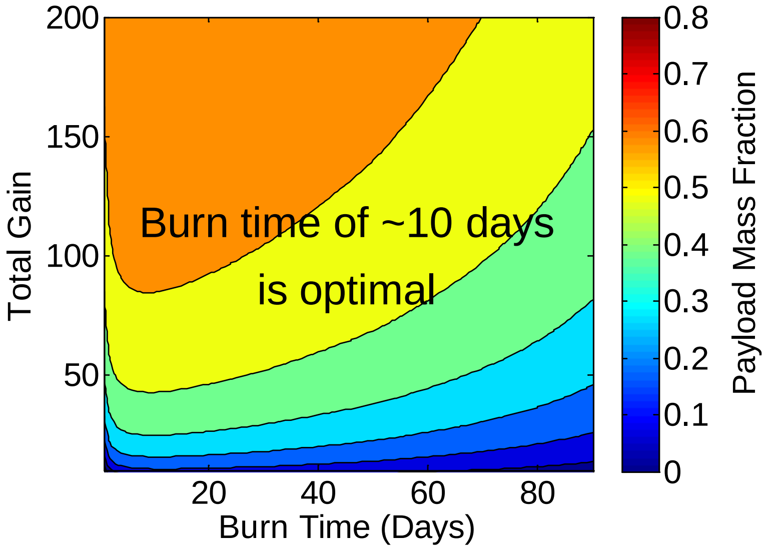
- Ionization cost is 75 MJ/kg
- Coupling Efficiency to liner is 50%
- Thrust conversion η_t ~ 90%
- Realistic liner mass are 0.28 kg to 0.41 kg
  - Corresponds to a Gain of 50 to 500
- Ignition Factor of 5
- Safety margin of 2: $G_F = G_F$(calc.)/2

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



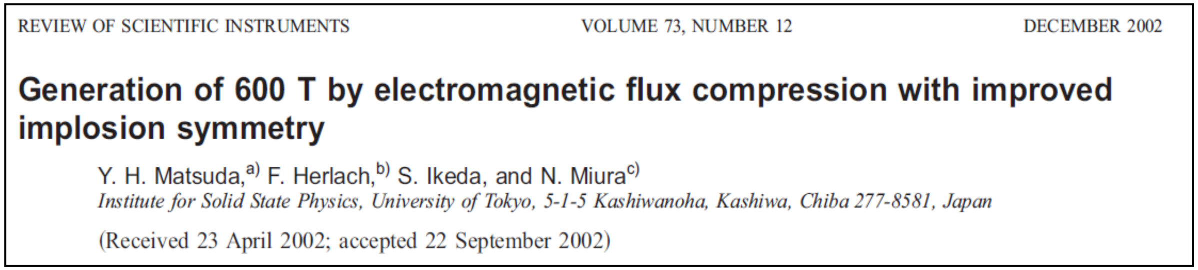
Higher fusion gain and longer trip times result in higher payload mass fraction



Burn time of ~10 days is optimal

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

Theoretical Validation of Key FDR Elements (peer reviewed papers)



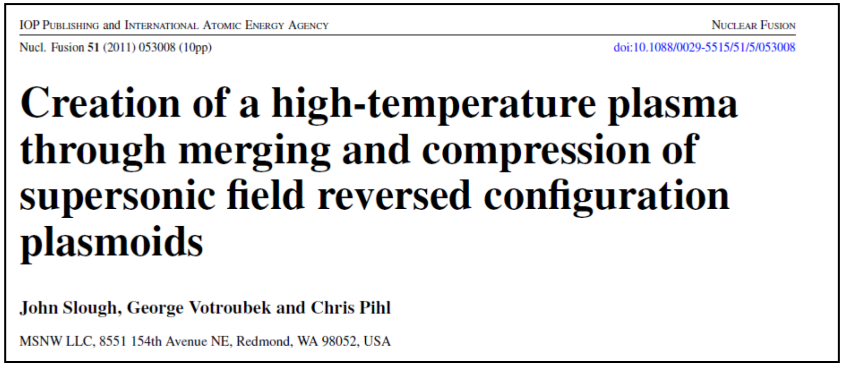
REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 73, NUMBER 12 DECEMBER 2002

Generation of 600 T by electromagnetic flux compression with improved implosion symmetry

Y. H. Matsuda,[a] F. Herlach,[b] S. Ikeda, and N. Miura[c]
Institute for Solid State Physics, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8581, Japan

(Received 23 April 2002; accepted 22 September 2002)

- Demonstrated inductively driven liner compression of B_z fields > 1 Mbar



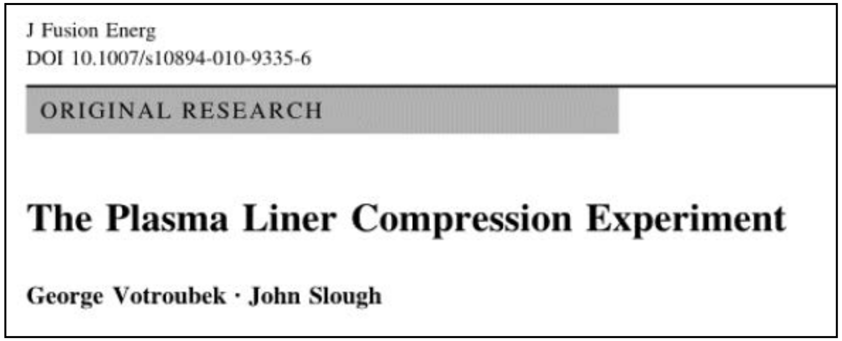
IOP Publishing and International Atomic Energy Agency Nuclear Fusion
Nucl. Fusion **51** (2011) 053008 (10pp) doi:10.1088/0029-5515/51/5/053008

Creation of a high-temperature plasma through merging and compression of supersonic field reversed configuration plasmoids

John Slough, George Votroubek and Chris Pihl

MSNW LLC, 8551 154th Avenue NE, Redmond, WA 98052, USA

- Demonstrated the stable formation, merging and magnetic compression of the FRC
- FRC lifetime better than previous scaling



J Fusion Energ
DOI 10.1007/s10894-010-9335-6

ORIGINAL RESEARCH

The Plasma Liner Compression Experiment

George Votroubek · John Slough

- Demonstrated successful FRC liner compression with a xenon plasma liner

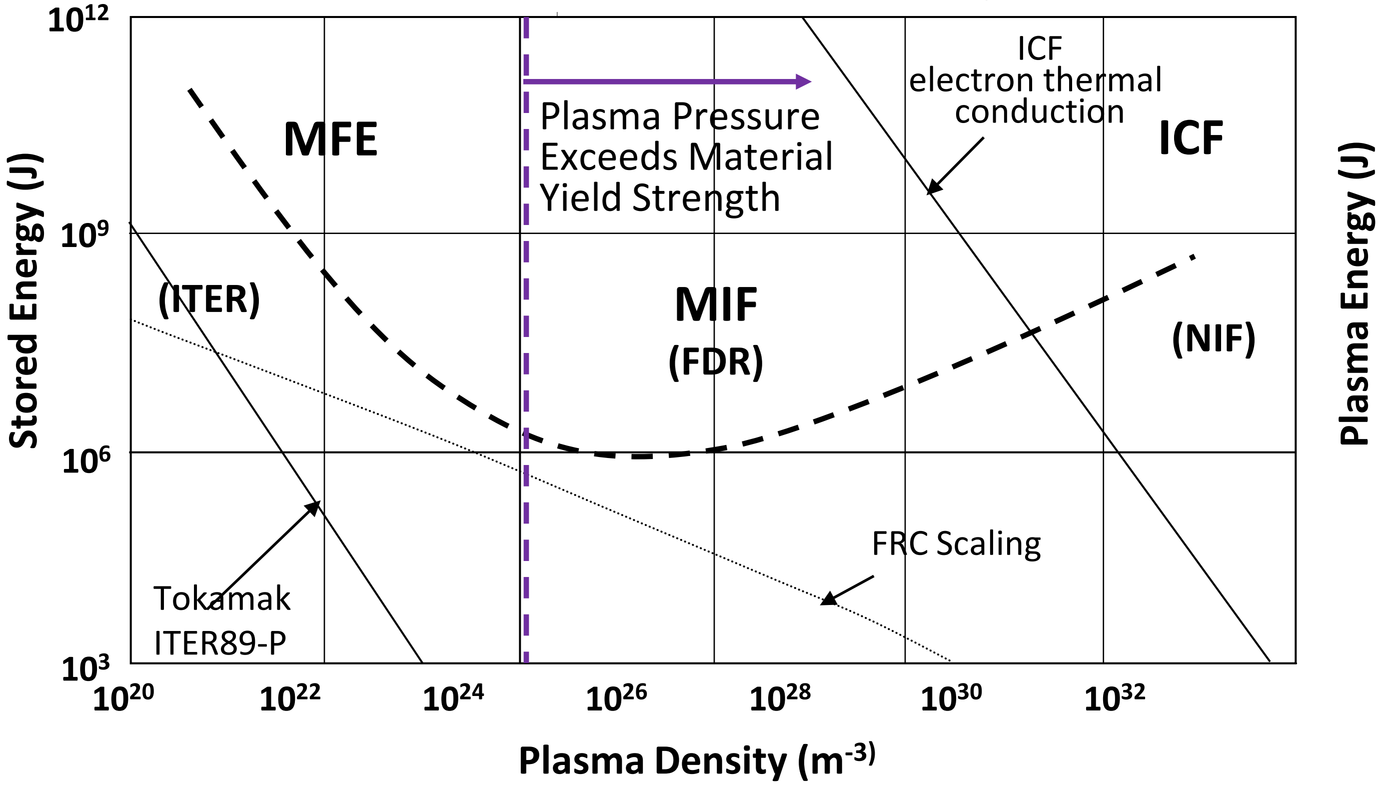
Experimental demonstration of fusion gain with inductively driven metal liners

Hope to publish in the near future!

Magneto-Inertial Fusion

Best of Both Worlds

Solid stars signify fusion gain conditions w $T_i = T_e = 10$ keV



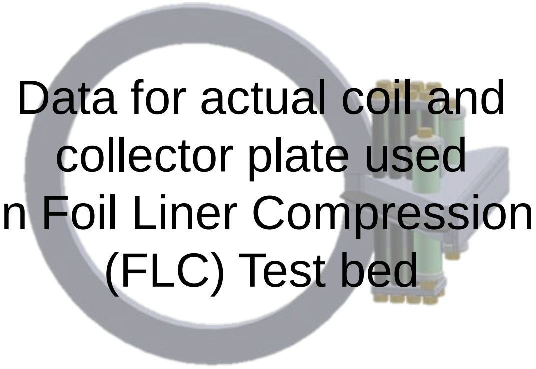
ITER MFE Issues:

- Enormous magnetic energy requires Cryogenic Magnets
- Low power densities leads to large scale, capital and development costs
- Devastating transient instabilities defy solution

NIF ICF Issues:

- Enormous storage energy (~400 MJ) due to very low driver efficiency
- Even with stand-off , reactor wall and is bombarded by primary fusion products
- Intricate and minute target with sub-nsec timing make for challenging technologies

1D Liner Code: Maxwell® Data

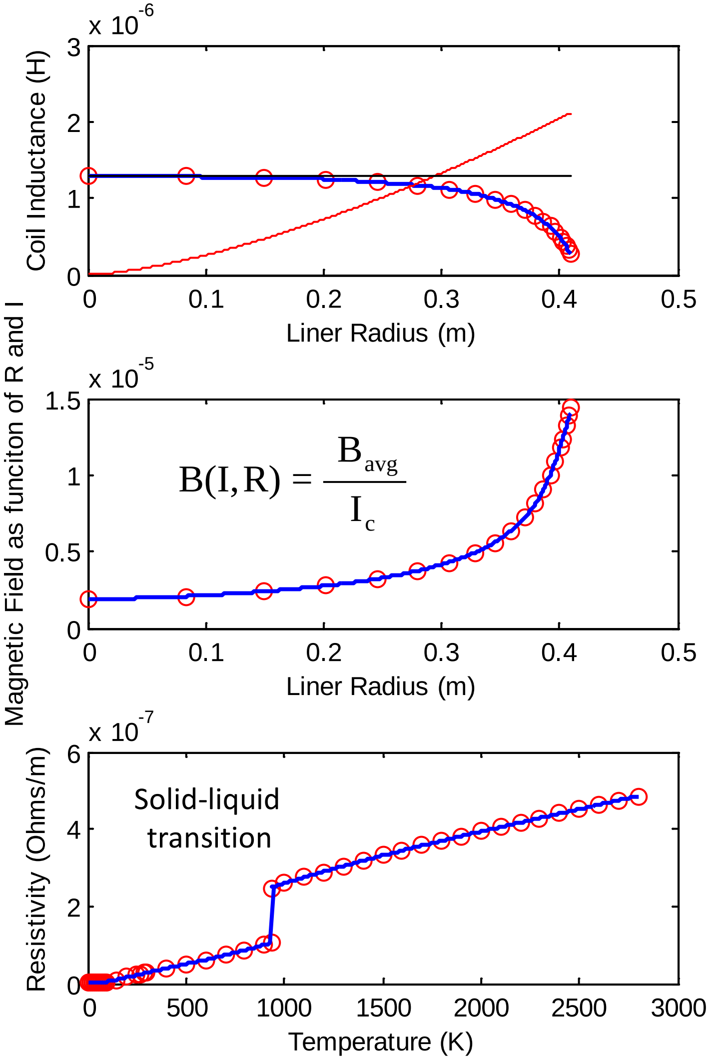


Data for actual coil and collector plate used In Foil Liner Compression (FLC) Test bed

Total Inductance of coil with liner at various locations. Liner inductance was determined theoretically

Average Magnet field in the gap between coil and liner divided by the current in the coil for various liner locations

Accurate definition of resistivity of Aluminum based on NIST data. Data only went to 2000 K. Data was linear extrapolated out to vaporization temperature



Physical Parameters

Description	Value
Circuit resistance	0.002 Ω
Magnet resistance	0.001 Ω
Circuit inductance	20e-9 H
Density of liner (Al)	2710 kg/m^3
Width of liner	0.06 m
Radius of coil	0.41 m
Initial radius of liner	0.403325 m
Voltage	40,000 V
Capacitance	420 u F
Liner thickness	0.2 mm

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

1D Liner Code
Conservation of Energy

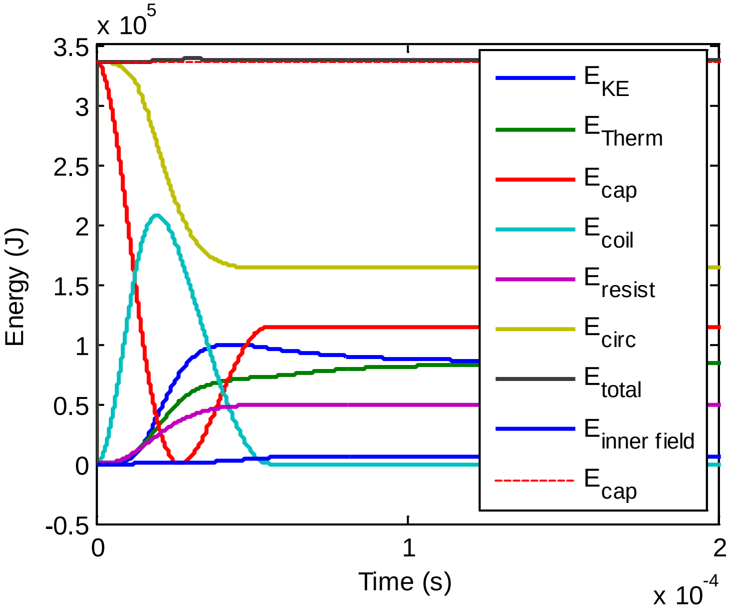
$$R = R_c + R_m + R_{KE} + R_T$$

Resistance of the coil

Resistance of the circuit

equivalent resistance value to remove the energy from the circuit equal to the kinetic energy gained by the liner

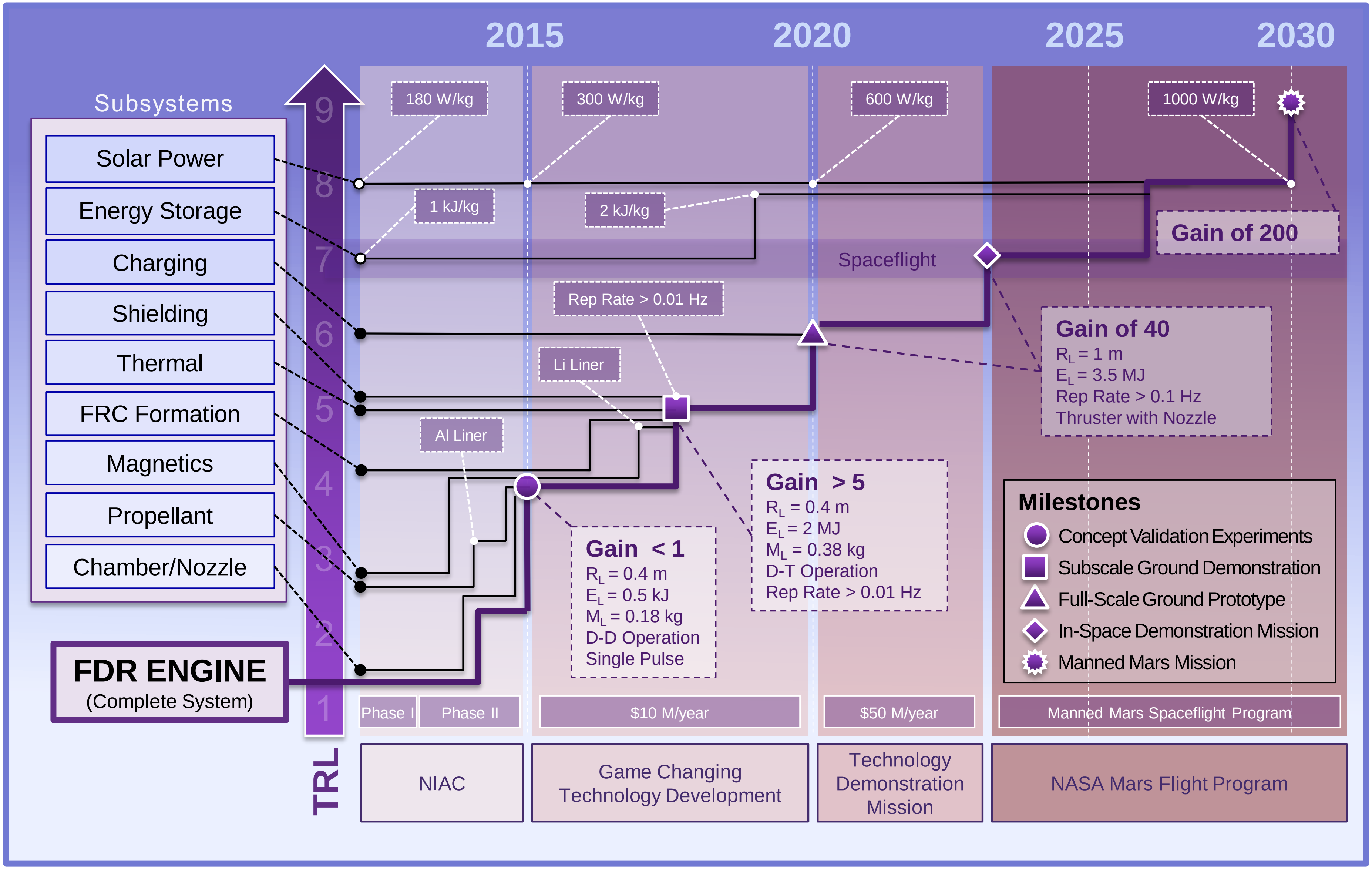
equivalent resistance value need to remove energy equal to ohmic dissipation (heating) of the liner



- Energy recovery
- All thermal losses
    - drive current
    - inner field current
- Pressure balance of inner and outer fields

Research Plan

Technology Roadmap for the Fusion Driven Rocket



2015 2020 2025 2030

Subsystems

- Solar Power
- Energy Storage
- Charging
- Shielding
- Thermal
- FRC Formation
- Magnetics
- Propellant
- Chamber/Nozzle

FDR ENGINE
(Complete System)

TRL 1 2 3 4 5 6 7 8 9

180 W/kg
300 W/kg
600 W/kg
1000 W/kg
1 kJ/kg
2 kJ/kg
Rep Rate > 0.01 Hz
Li Liner
Al Liner
Spaceflight

Gain < 1
R_L = 0.4 m
E_L = 0.5 kJ
M_L = 0.18 kg
D-D Operation
Single Pulse

Gain > 5
R_L = 0.4 m
E_L = 2 MJ
M_L = 0.38 kg
D-T Operation
Rep Rate > 0.01 Hz

Gain of 40
R_L = 1 m
E_L = 3.5 MJ
Rep Rate > 0.1 Hz
Thruster with Nozzle

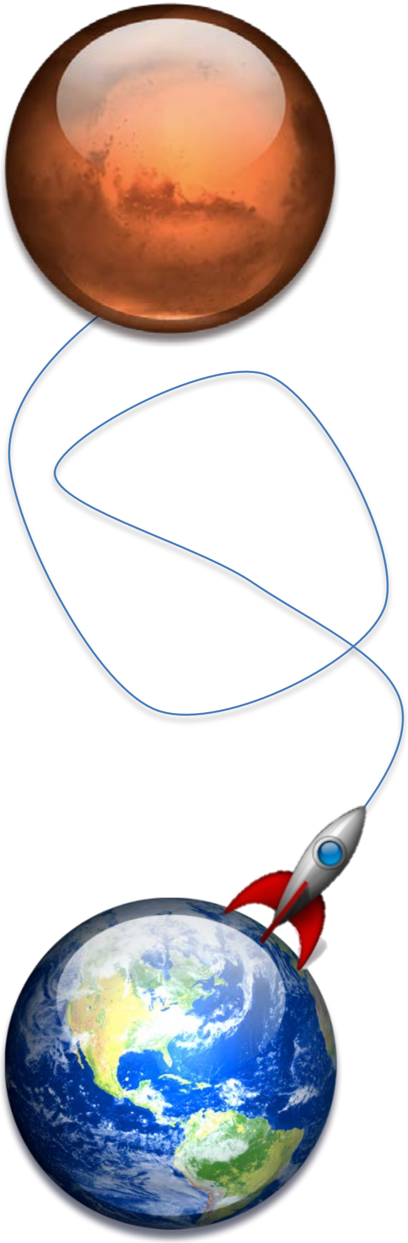
Gain of 200

Milestones

- ● Concept Validation Experiments
- ■ Subscale Ground Demonstration
- ▲ Full-Scale Ground Prototype
- ◆ In-Space Demonstration Mission
- ✹ Manned Mars Mission

Phase I	Phase II	$10 M/year	$50 M/year	Manned Mars Spaceflight Program
NIAC		Game Changing Technology Development	Technology Demonstration Mission	NASA Mars Flight Program

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?

Analytical Model (Fusion Side)

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

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

From action Integral constraint where R_L= 1.2 m, w = 0.15m

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

Energy loss in ionization of liner (~75 MJ/kg)

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

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

E_{out} = fusion energy + E_{in}

E_L = liner kinetic energy

$E_{in} = E_L + E_{FRC} \cong E_L$

M_L = mass of liner

v_L = velocity of Liner

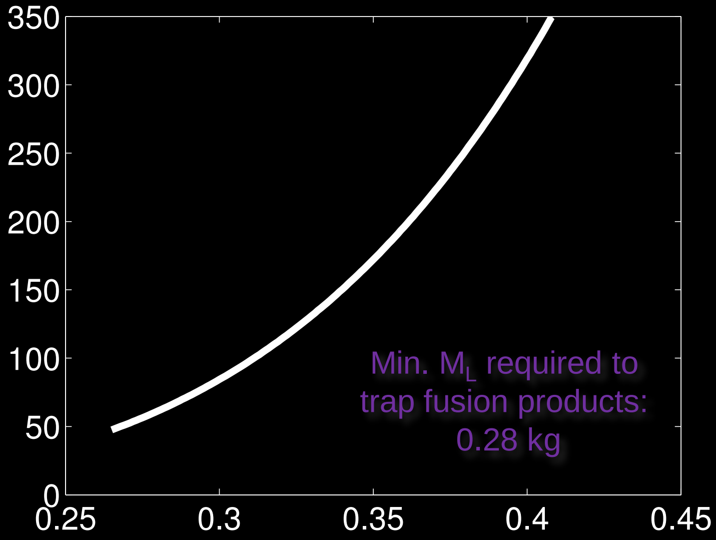
$\eta_C = E_L / E_{cap} = 0.5$

η_T = thrust efficiency = 0.9

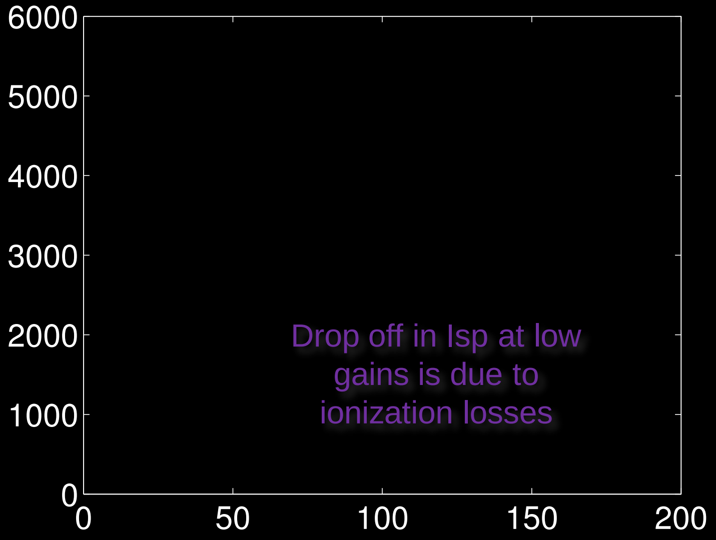
E_k = kinetic (Jet) energy

I_{sp} = specific impulse

For known
Liner Mass
a
Specific Impulse
is determined



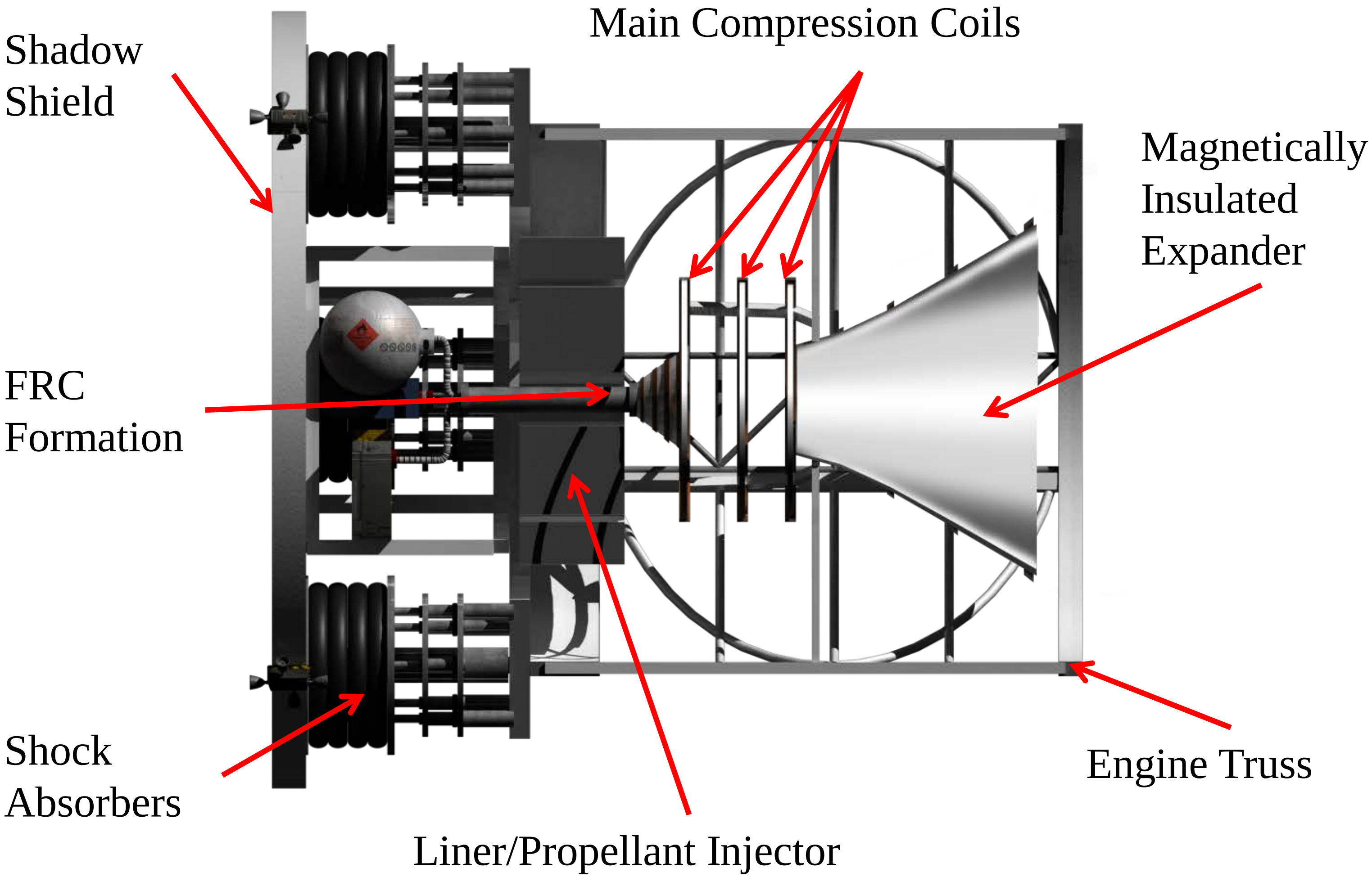
Min. M_L required to trap fusion products: 0.28 kg



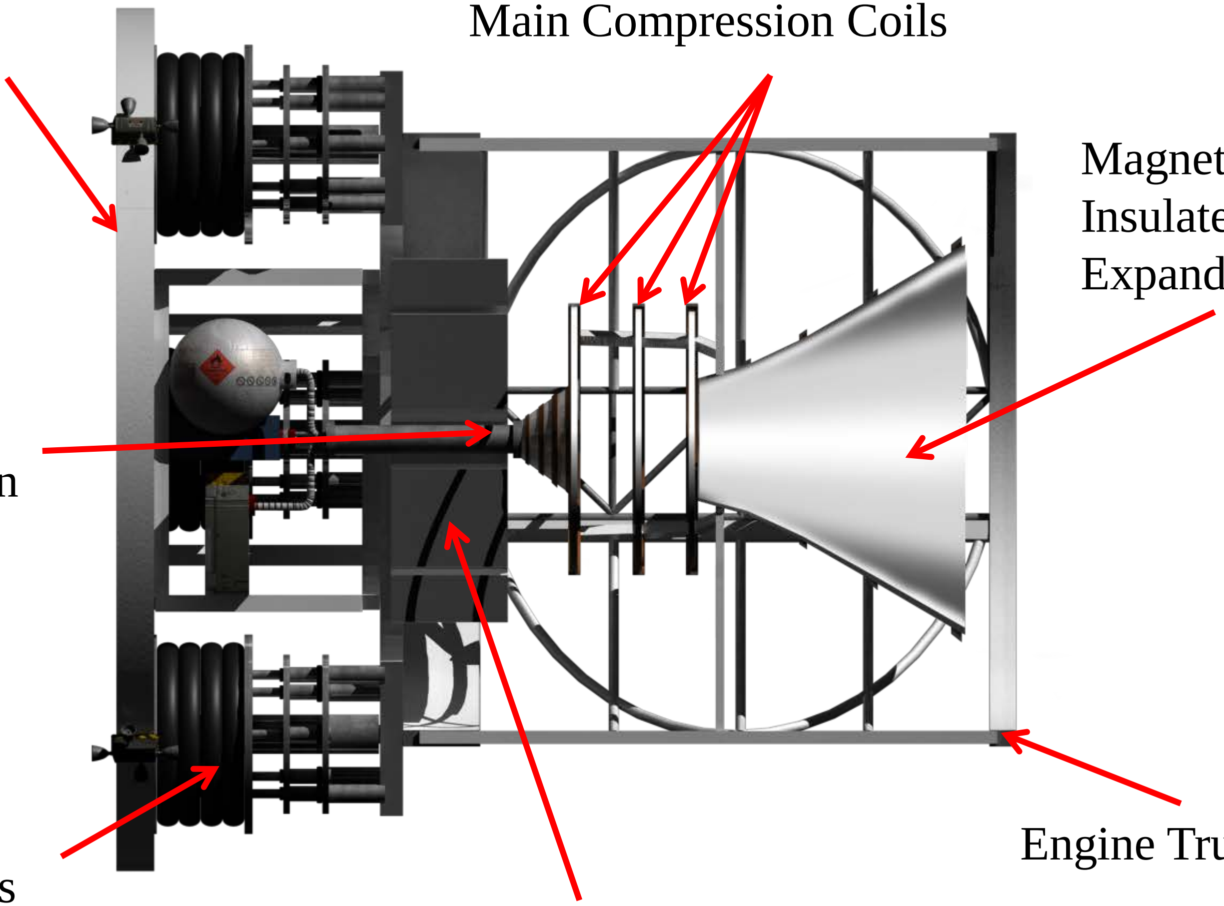
Drop off in Isp at low gains is due to ionization losses

Isp links fusion conditions with mission equations

Fusion Driven Rocket Engine



Fusion Driven Rocket Engine



Shadow Shield

Main Compression Coils

Magnetically Insulated Expander

FRC Formation

Shock Absorbers

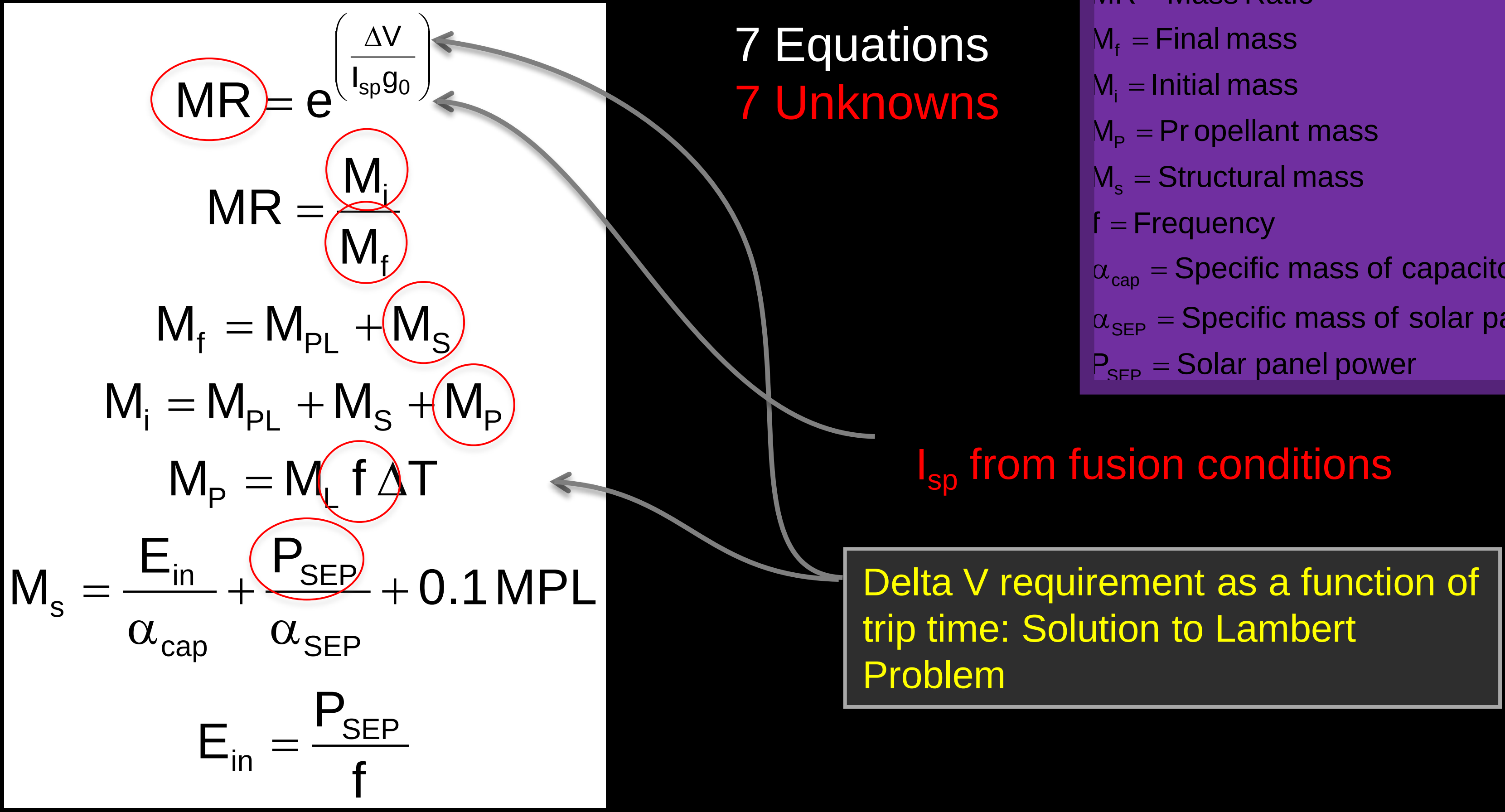
Engine Truss

Liner/Propellant Injector

Analytical Model

(Mission side)

Rocket Equations



$$\boxed{MR} = e^{\left(\frac{\Delta V}{I_{sp} g_0}\right)}$$

$$MR = \frac{\boxed{M_i}}{\boxed{M_f}}$$

$$M_f = M_{PL} + \boxed{M_S}$$

$$M_i = M_{PL} + M_S + \boxed{M_P}$$

$$M_P = M_L \boxed{f} \Delta T$$

$$M_s = \frac{E_{in}}{\alpha_{cap}} + \frac{\boxed{P_{SEP}}}{\alpha_{SEP}} + 0.1\,MPL$$

$$E_{in} = \frac{P_{SEP}}{f}$$

7 Equations

7 Unknowns

MR = Mass Ratio

M_f = Final mass

M_i = Initial mass

M_P = Propellant mass

M_s = Structural mass

f = Frequency

α_{cap} = Specific mass of capacitors

α_{SEP} = Specific mass of solar panels

P_{SEP} = Solar panel power

I_{sp} from fusion conditions

Delta V requirement as a function of trip time: Solution to Lambert Problem

- It is assumed that initially FDR employs solar panels for house keeping power
- Eventually it would be derived directly from nozzle flux compression