
The Fusion Driven Rocket
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Why We Are Not on Mars Yet?

Takes too long (914 days) **Costs too much** (> 20$B)

Safety

Radiation exposure
Cancer risk

Mental fatigue

Bone & muscle loss

Increased risk of critical failure

Mission

Operational costs:

- Complexity
- Asset Pre-deployment
- Space assembly

Political

Governmental support

Public interest

Launch

Large space structures

Huge fuel Mass

New method of propulsion is needed:

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

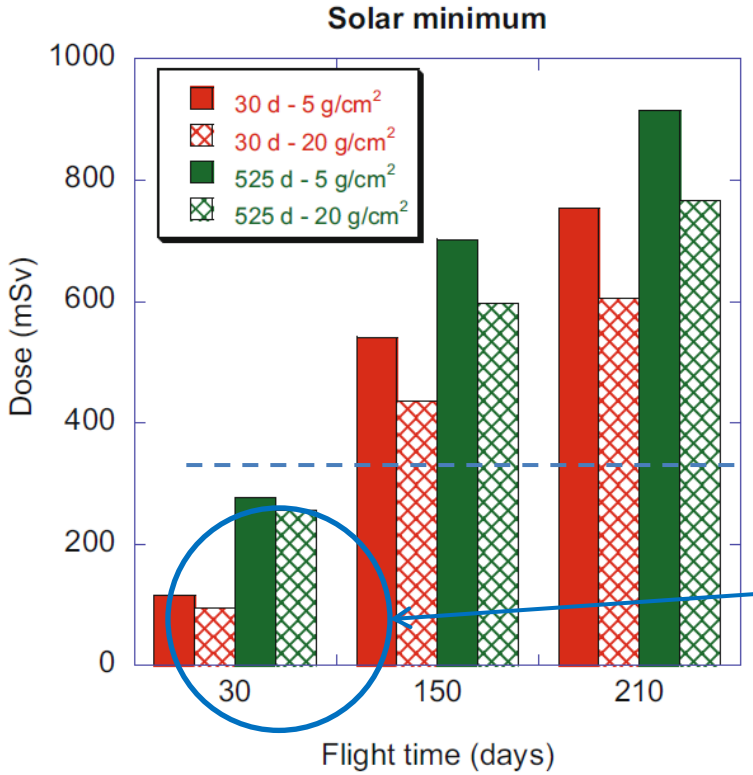
Reduced IMLEO → High Exit Velocity (I_{sp})

$\frac{\text{Engine Power}}{\text{Spacecraft Mass}}$

Estimated Total Equivalent Doses for a Mars Mission

Mars sortie mission (30 days stay)

Long stay at Mars base (525 days)



Current technology (210 days)

Nuclear thermal/electric reactor (150 days)

Fusion Driven Rocket (FDR) (30 days)

Solid bars – calculation for spacecraft with a minimum shield (5 g/cm² Al)
Dashed bars – calculations for a thick shield (20 g/cm² Al)

➢ The career limit is 400 mSv for a 25 year old with a 3% risk of fatal cancer

J. Slough, "Spacecraft Scale Magnetospheric Protection from Galactic Cosmic Radiation," 2022 IEEE Aerospace Conference (AERO), Big Sky, MT, USA, 2022, pp. 1-19, doi: 10.1109/AERO53065.2022.9843210

Trip Time for Direct Mission to Mars

Accelerating the spaceship mass M_{ss} over a time τ implies a power P where:

$$P_j \approx \frac{M_{ss} v_c^2}{2\tau}$$

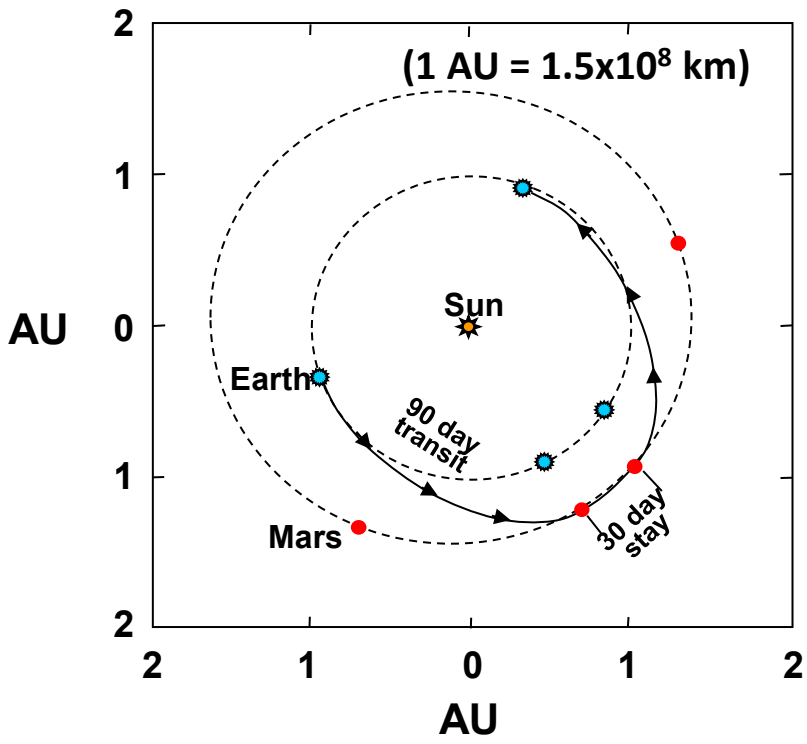
One defines a characteristic velocity v_c:

$$v_c = (2\alpha\tau)^{1/2}$$

where a_P is the specific power:

$$\alpha_P = \frac{P_j}{M_{ss}} = \alpha_M^{-1}$$

with α_M the specific mass.



The the trip time, τ_{trip}, to go a distance L is

$$\tau_{trip} \approx 2\frac{L}{v_c} \quad \text{or} \quad \tau_{trip}(\text{days}) \cong 51.6\left[\alpha_M(\text{kg/kW})L^2(\text{AU})\right]^{1/3}$$

For the 90 day Mars transit (L ~ 1.5 AU) requires $\alpha_P >\sim 0.4$

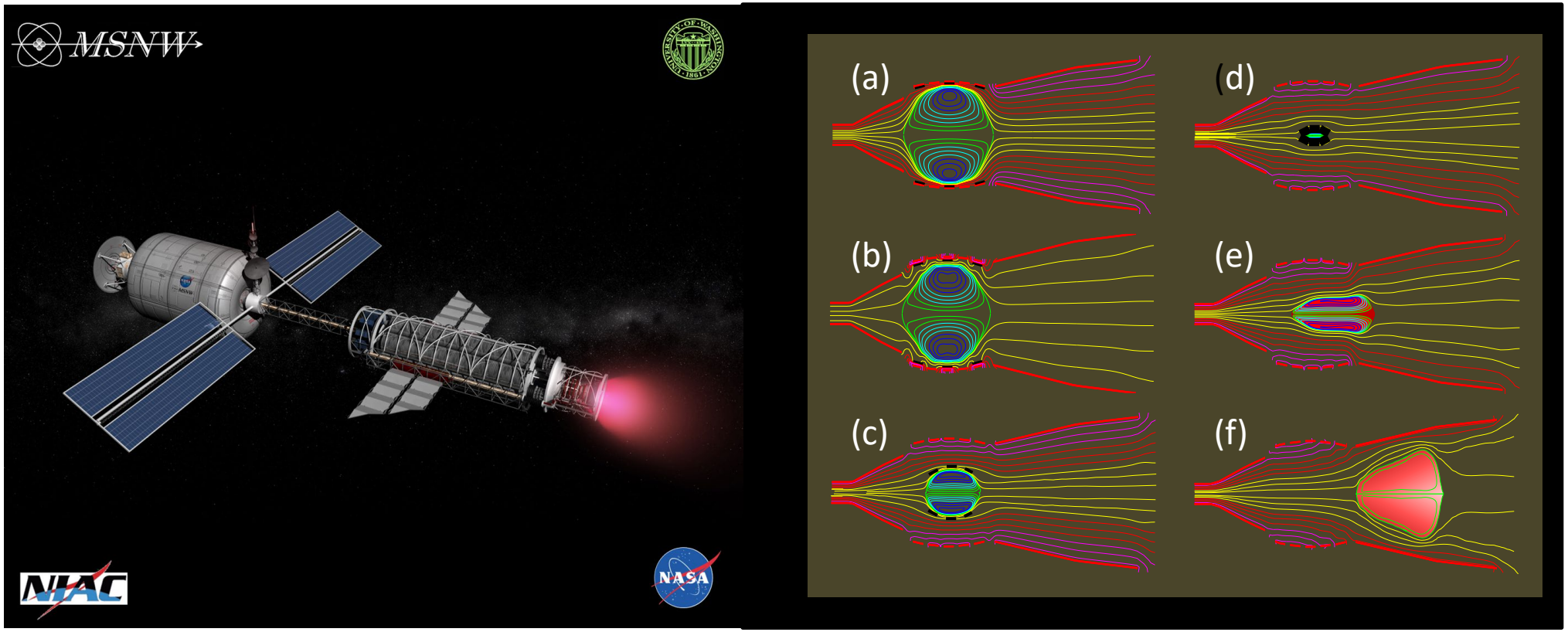
For the 30 day Mars transit (L ~ 0.7 AU) requires $\alpha_P >\sim 2.5$

FDR:

$0.3 < \alpha_P < 3.0$

The Fusion Driven Rocket:

Propulsion through Direct Conversion of Nuclear Fusion Energy



- Virtually all fusion, radiation, plasma Energy DIRECTLY deposited into Lithium propellant
- Large external magnetic flux provides spacecraft protection from plasma and nuclear process
- Isolation and high-efficiency thermal conversion eliminates need for large radiator mass
- Solid propellant drastically reduces storage mass and reactive propellant leakage risk
- Pulsed operation provides variable power profile with high thrust at optimal Isp

Steps Involved in the Process of Generating the Fusion-Driven Propulsion System

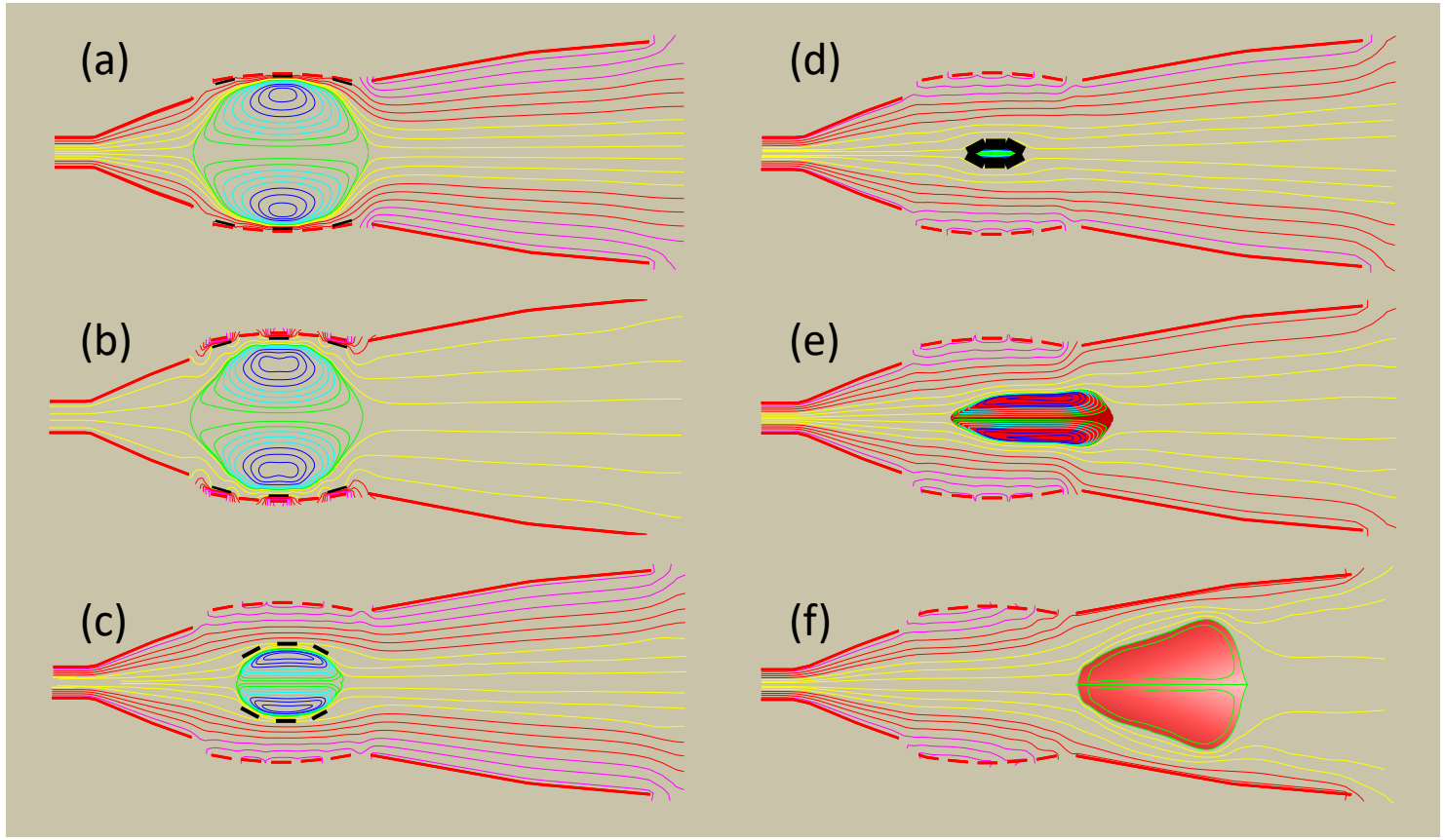
(a) FRC plasmoid generated inside the thruster by external RF antennas

(b) Plasmoid fueled radially by injecting frozen pellets of Deuterium and Tritium

(b)-(d) Bands of Lithium are inductively driven inward to high velocity by external magnetic coils

(c)-(d) the converging bands compress the plasmoid to fusion conditions

(d) the thick shell formed by the bands capture the fusion product energy as well as that of the plasma and radiation



(e) The immense energy release vaporizes and ionizes the Lithium shell creating a bolus of plasma at the central axis of a strong, divergent magnetic field created by the driver coils and nozzle coils.

(f) The lithium plasma thermal energy is efficiently converted to directional thrust and high Isp as it transits and expands out of the magnetic nozzle.

Step 1: Generation of an FRC plasmoid with an External RF Rotating Magnetic Field (RMF)

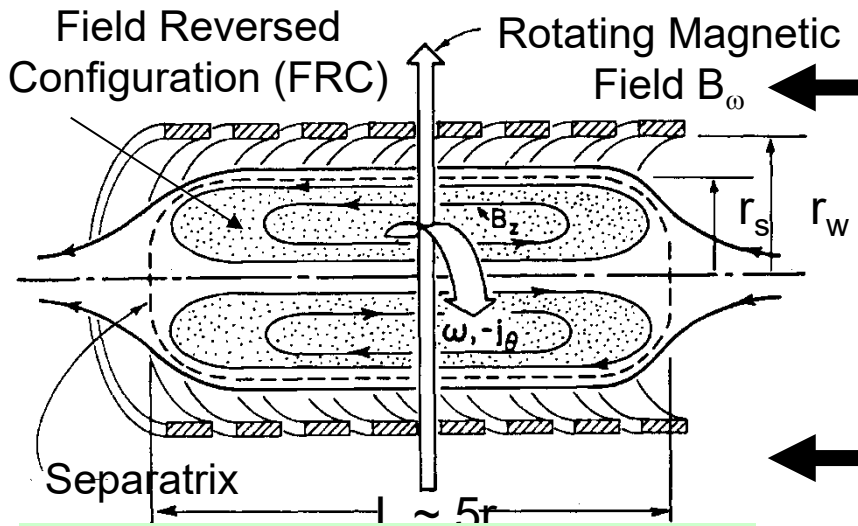
Key Physics:

RMF frequency is such that the electrons are magnetized to the field, but the ions, due to their much greater inertia are not, i.e.

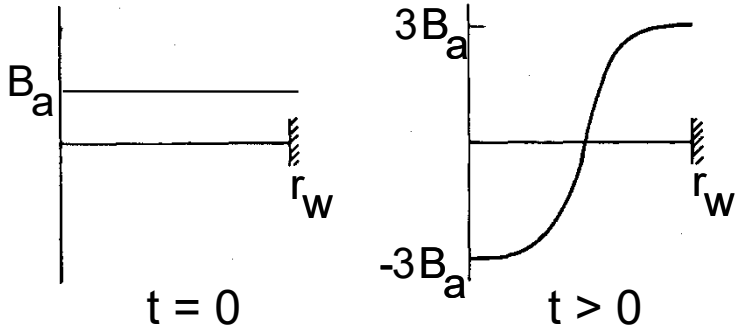
$$\omega_{ci} \ll \omega_{RMF} \ll \omega_{ce}$$

ion cyclotron frequency

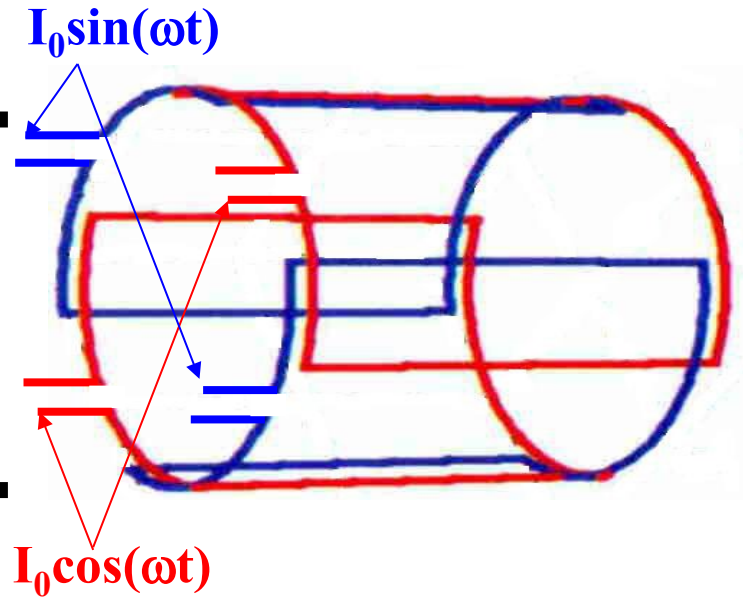
electron cyclotron frequency



Synchronous electron motion
$\Rightarrow j_\theta(r) = e\, n_e\, \omega\, r$



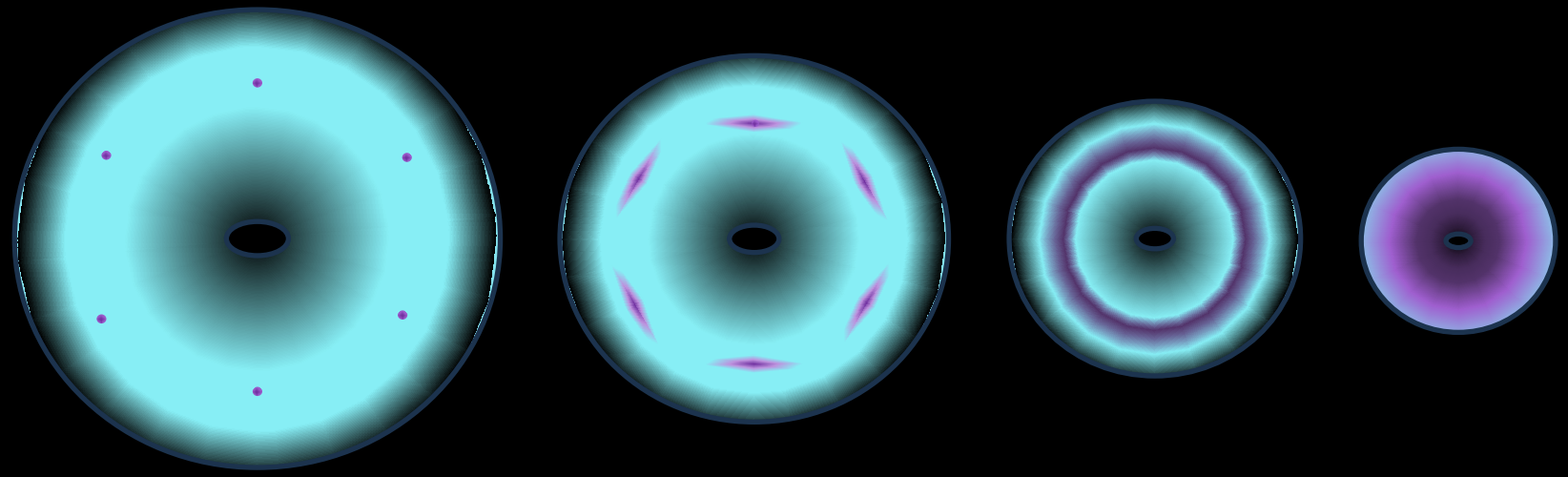
Initial axial magnetic field B_a is reversed by synchronous J_θ current driven by RMF



m=1, "saddle" antenna coils are positioned radially external to the axial field coils. Two oscillators phased at 90° produce a constant amplitude rotating field B_ω.

Step 2: DT Pellet Fueling During Band Compression of the FRC

Pellets are composed of frozen hydrogen isotopes (tritium and deuterium) and accelerated with light gases (H and He) to speeds up to 3 km/s



DT pellets are injected at 6 ports about the midplane for azimuthal symmetry

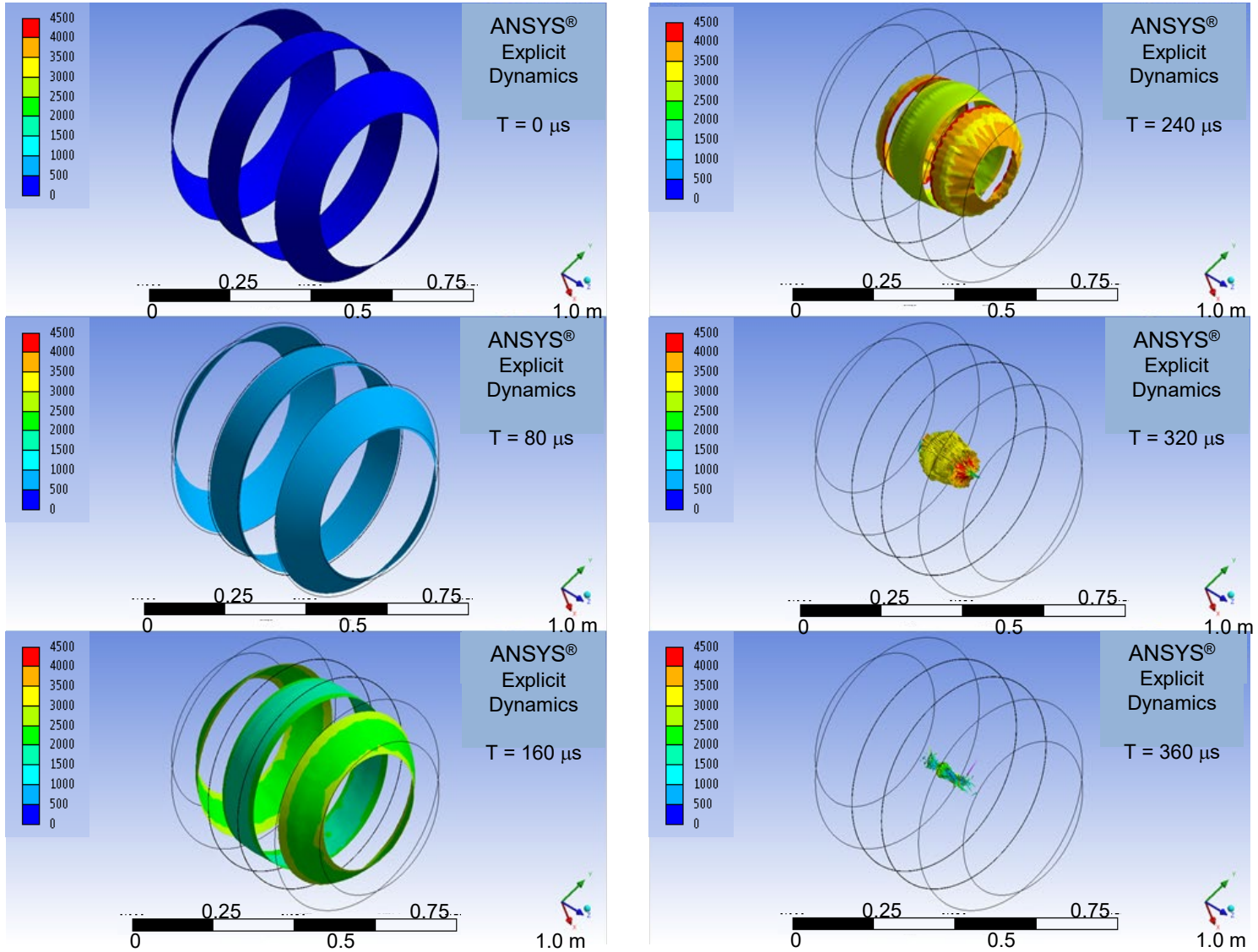
Final FRC Inventory:

$N_{DT} \sim 2\times10^{20} \Rightarrow$ (6) 1mm pellets (same as original ISX-B experiment)

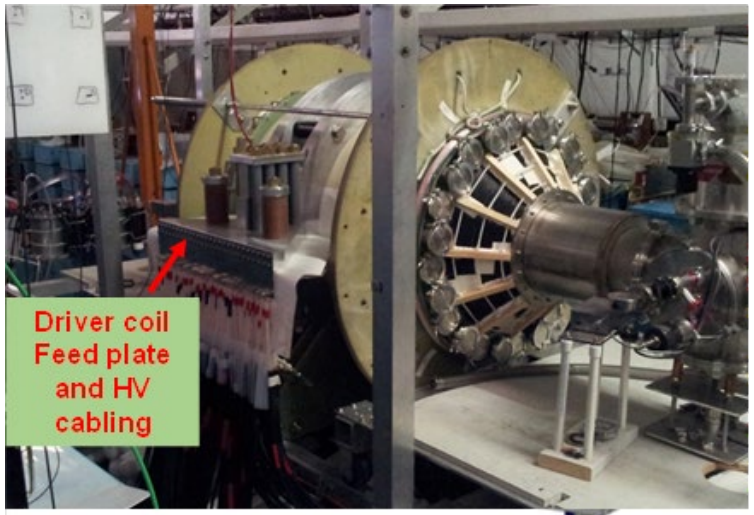
- DT Pellet fueling brings high-flux, low density RMF FRC to high density
- Pellet inward radial velocity is matched to that of the bands (~ 2 km/sec)
- Ablation thus occurs primarily at FRC null region ⇒

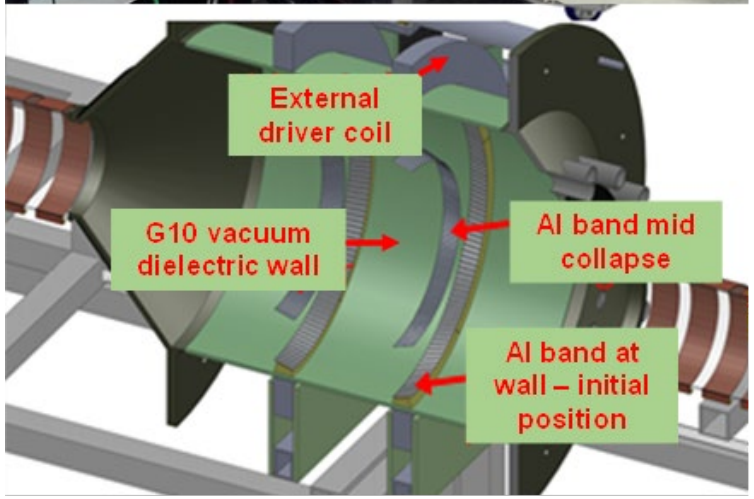
Step 3: Li Bands Inductively Driven to Compress FRC Compressing to High Field (500 T) and Fusion Gain

3D ANSYS Explicit Dynamics® calculations of the convergent implosion of three metal bands

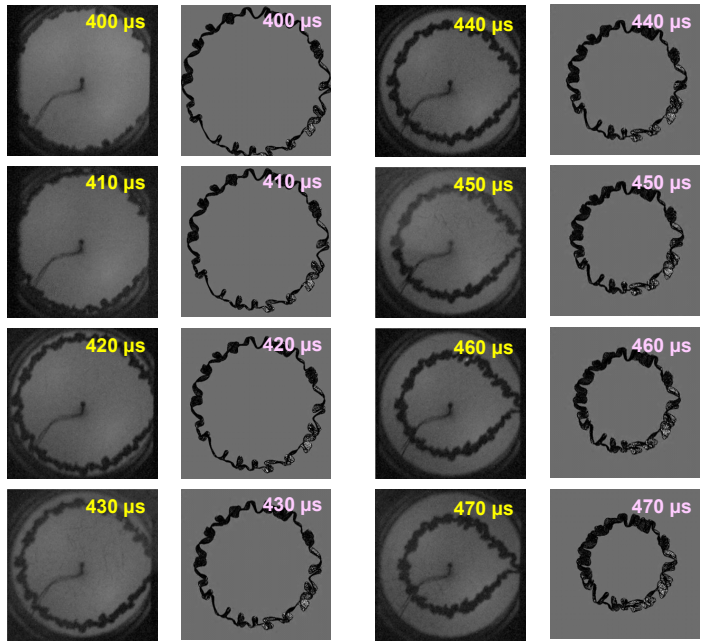


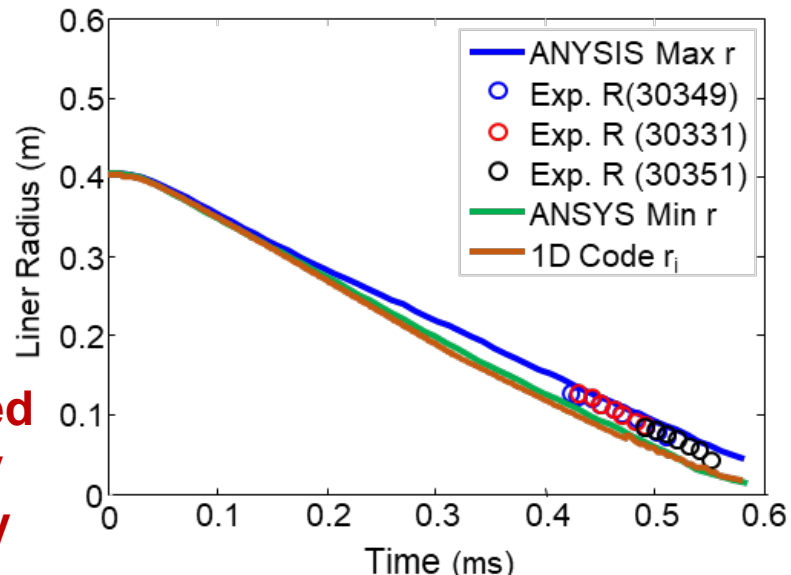
Experimental Validation of the Large-Scale Band Compression Method





Large scale metal band compression test bed for FDR validation experiments at University of Washington Plasma Dynamics Laboratory





Experimental End-on images (left) and AEDS code results (right) for a 0.4 m radius, 0.16 kg aluminum band.

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

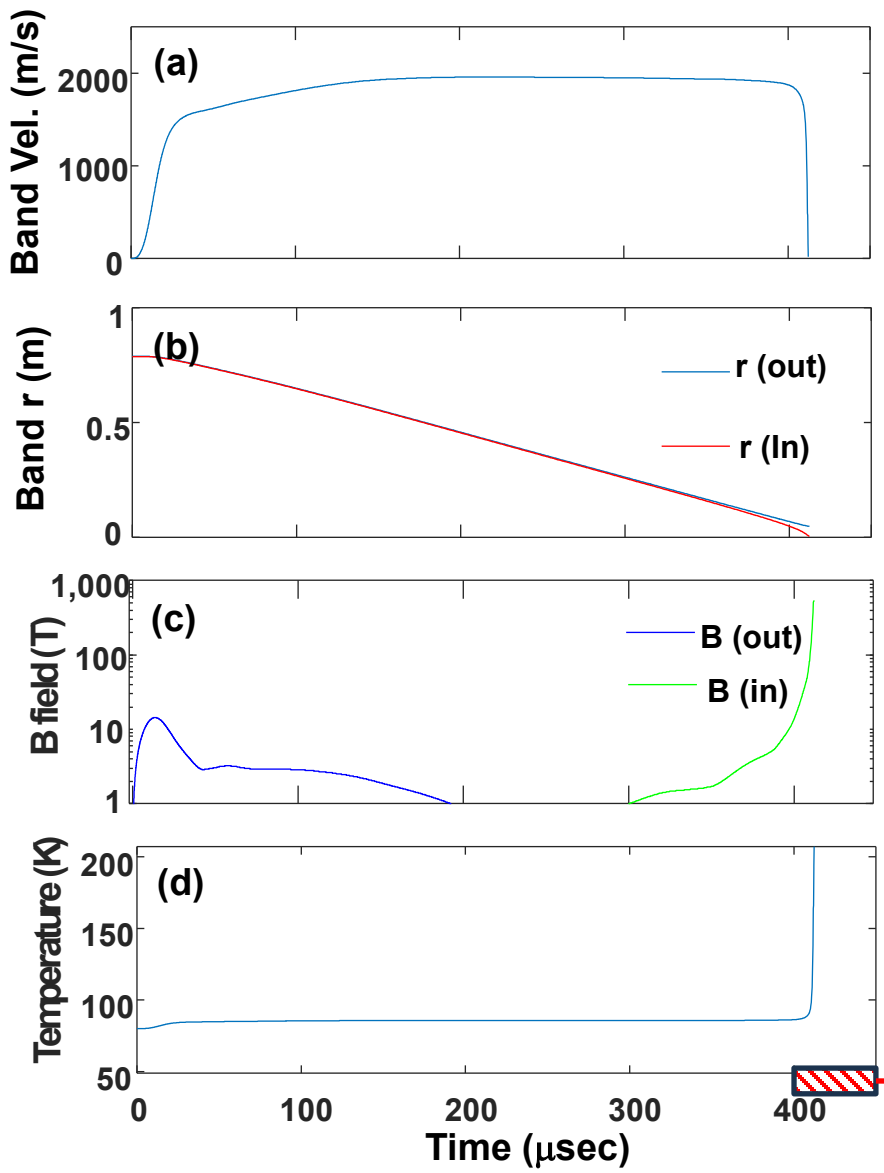
Code Optimization of the Inductively Driven Band Compression Driver System for Fusion Gain

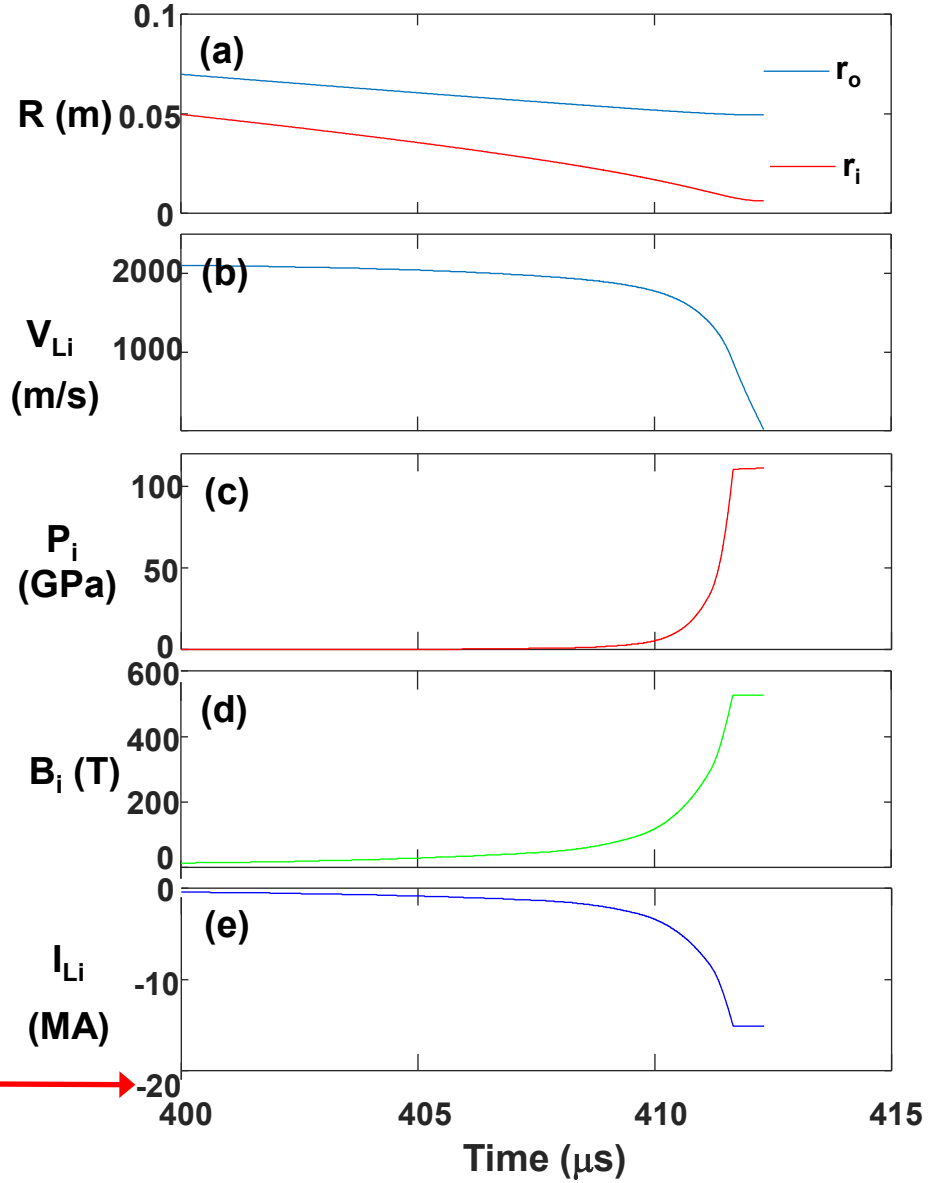
Initial Values	
Driver Coil Radius	0.80 m,
Initial Li band Radius	0.79 m
Li band thickness	1.5 mm
Initial band Temperature	80 °K
Initial band flux	0.1 Wb
Initial band internal B_i	5.0 mT
Driver cap. C	0.5 mF
Driver Volt. V	60 kV

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}	1,960 m/s
Final r_i inside shell	6.27 mm
Final shell r_o	48.5 mm
η_{eff} (Li band E_k /ΔE_{driver})	90.2 %
Final shell Temp:	208.01 °K

$$G = \frac{E_{fus}}{E_{Li}} = 16.0\, B_i^2 \frac{r_o}{v_{Li}}$$

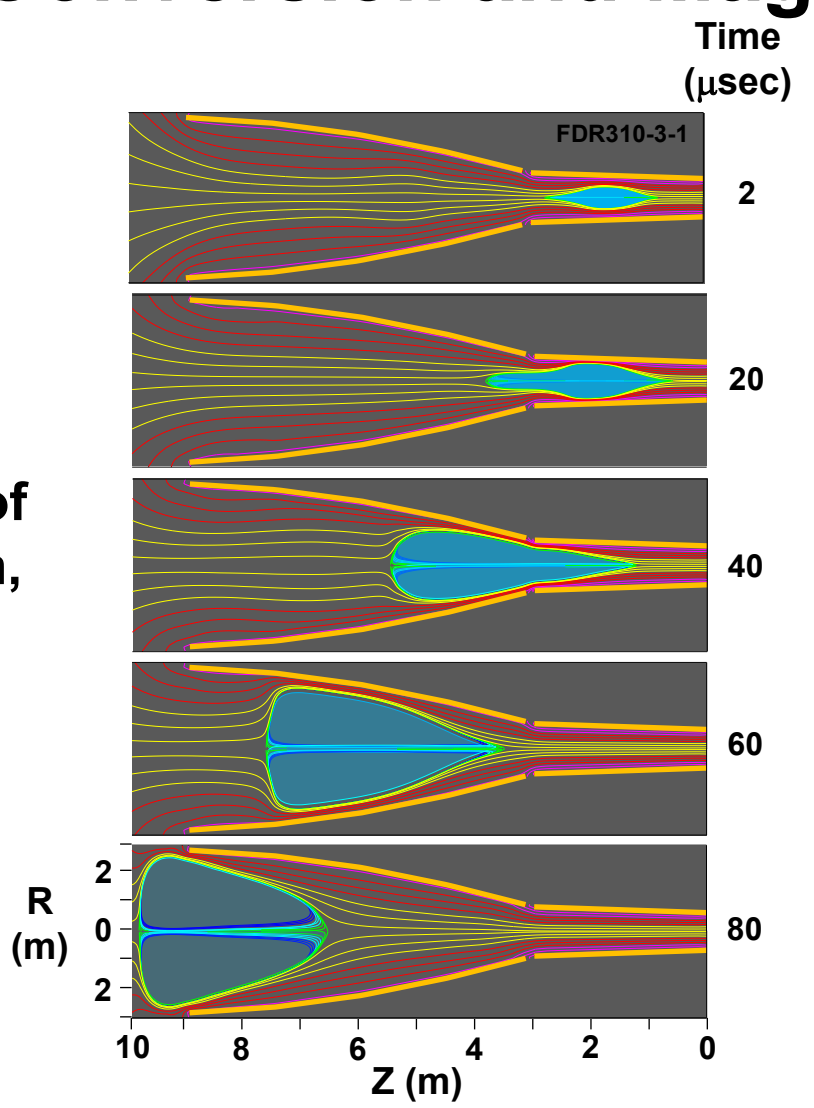
$$v_{jet} = \sqrt{f_c G_{eff}}\, v_{Li} = 34.0 \frac{km}{s}$$

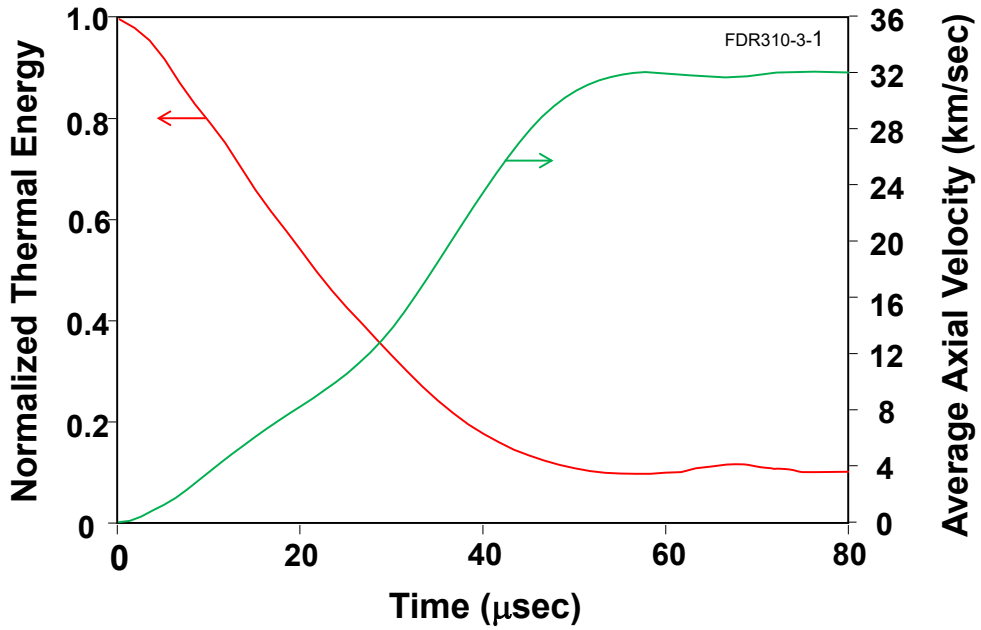




Fusion Energy Conversion and Magnetic Nozzle Physics

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.





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.

Manned Mars Mission Analysis

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

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

Manned Mars Mission Analysis

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

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

Fusion Driven Rocket to Mars

