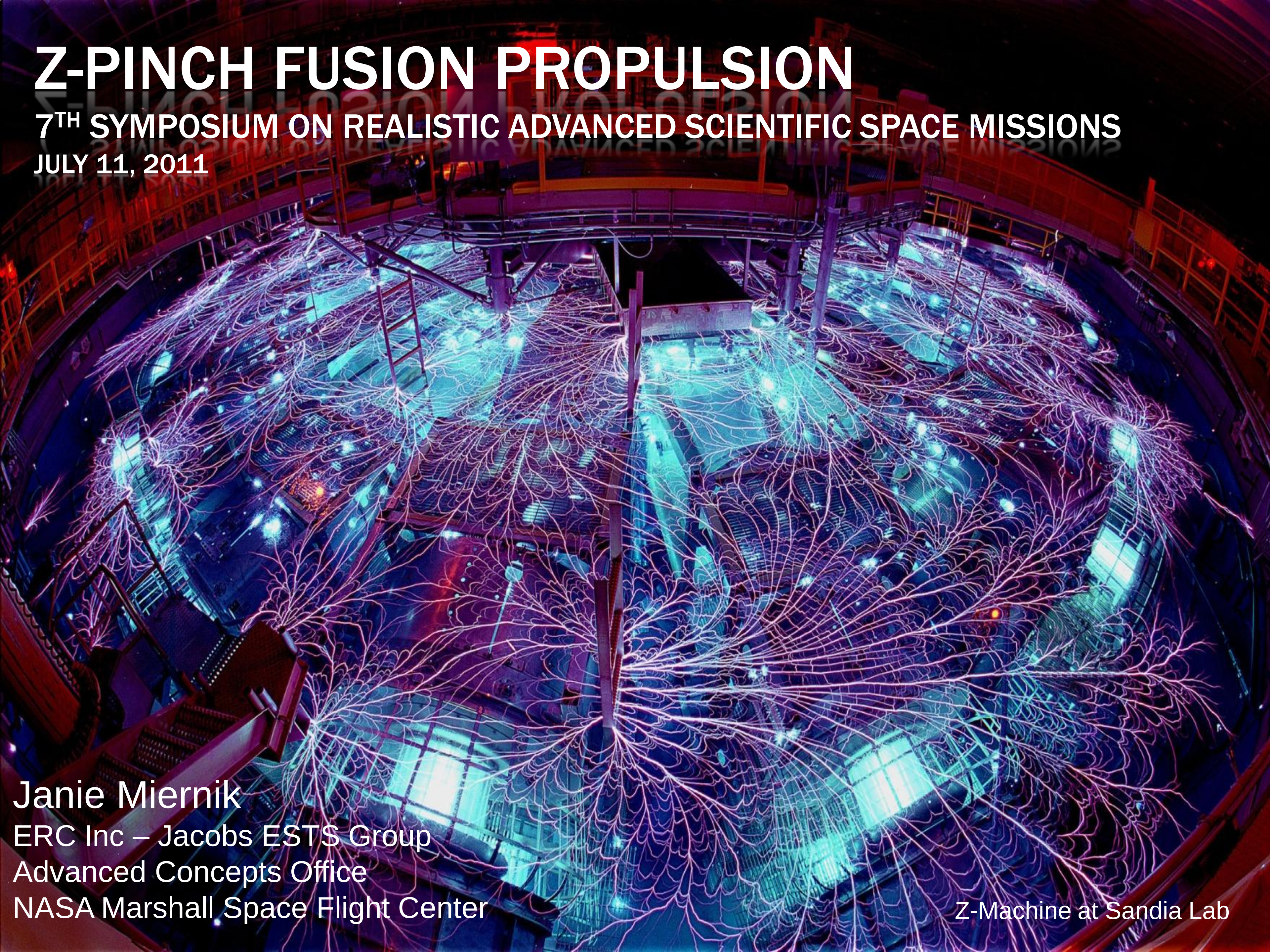
Z-PINCH FUSION PROPULSION

7TH SYMPOSIUM ON REALISTIC ADVANCED SCIENTIFIC SPACE MISSIONS

JULY 11, 2011



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Z-Machine at Sandia Lab

FUSION PROPULSION

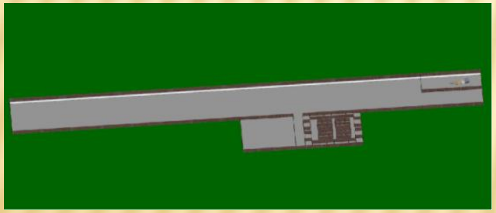
- Fusion-based nuclear propulsion has the potential to enable fast interplanetary transportation.
- Shorter trips are better for humans in the harmful radiation environment of deep space.
- Nuclear propulsion and power plants can enable high I_{sp} and payload mass fractions because they require less fuel mass.
- Fusion energy research has characterized the Z-Pinch dense plasma focus method.
  - Lightning is form of pinched plasma electrical discharge phenomena.
  - Wire array Z-Pinch experiments are commonly studied and nuclear power plant configurations have been proposed.
  - Used in the field of Nuclear Weapons Effects (NWE) testing in the defense industry, nuclear weapon x-rays are simulated through Z-Pinch phenomena.

NWE TEST ARTICLE – DM2*

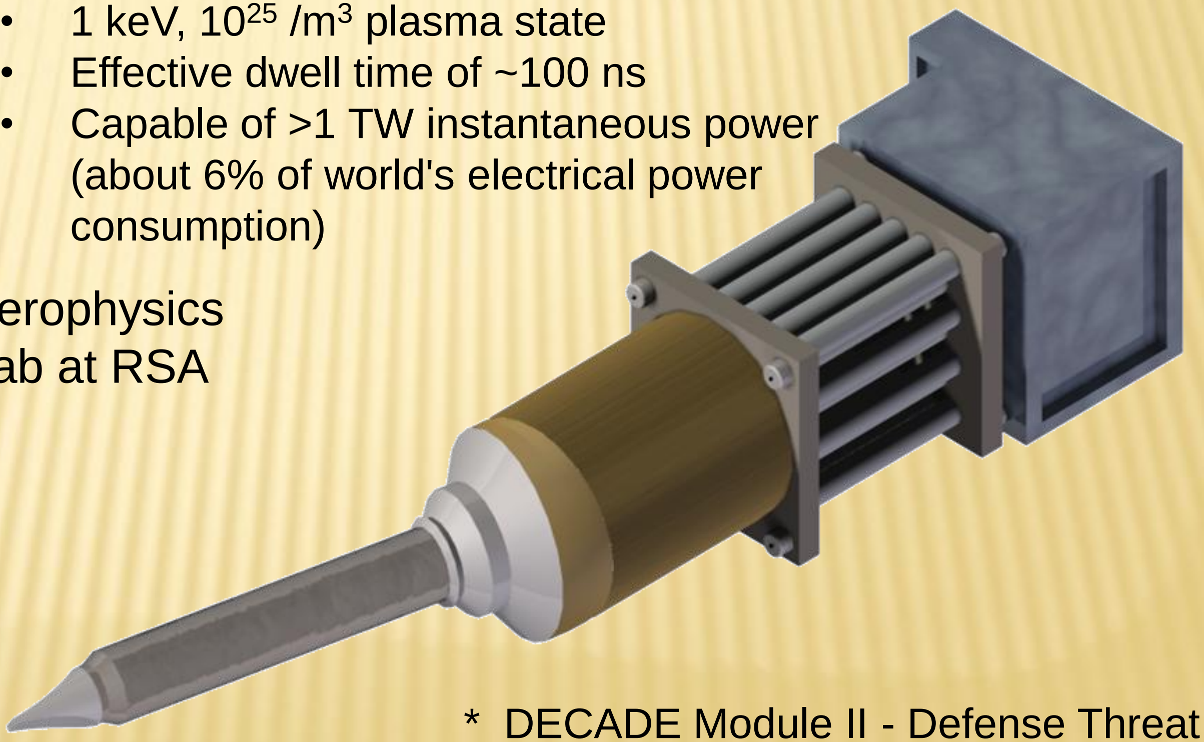
DM2 modules made up the Z-Machine at Sandia National Laboratories, New Mexico, USA

Expected DM2 Capabilities:

- 500 ns pulse, 2 MA current
- 1 keV, 10^{25} /m^3 plasma state
- Effective dwell time of ~100 ns
- Capable of >1 TW instantaneous power (about 6% of world's electrical power consumption)



Aerophysics Lab at RSA



* DECADE Module II - Defense Threat Reduction Agency, circa 1995

PREVIOUS FUSION PROPULSION STUDIES

Concept	α (kW/kg)	n (#/m^3)	Freq. (Hz)	Mass (mT)	Source
Steady State					
Quiet Electric Discharge (QED)	12	n/a	n/a	500	(Bussard and Jameson 1994)
Inertial Electrostatic Confinement (IEC)	0.02	n/a	n/a	300	(Miley, Satsangi et al. 1994)
Gas Dynamic Mirror (GDM)	10	1.0×10^{22}	n/a	1225	(Emrich 2003)
Tandem Mirror (SOAR)	1.2	5.0×10^{19}	n/a	1220	(J.F. Santarius 1998)
Spheromak	5.75	8.0×10^{20}	n/a	1050	(Borowski 1994)
Field Reversed Configuration (FRC)	1	1.0×10^{21}	n/a	1100	(H. Nakashima 1994)
Colliding Beam FRC	1.5	5.0×10^{20}	n/a	33	(Cheung, Binderbauer et al. 2004)
Dipole	1	1.0×10^{19}	n/a	1300	(Teller, Glass et al. 1992)
Spherical Torus	8.7	5.0×10^{20}	n/a	1630	(Williams, Dudzinski et al. 2001)
Pulsed					
Inertial Fusion Rocket (IFR)	70	1.0×10^{25}	100	760	(Borowski 1994)
Inertial Confinement Fusion (ICF)	3.4	1.0×10^{25}	30	5800	(Orth and al. 1987)
Magnetized Target Fusion (MTF)	1.12	1.0×10^{26}	20	890	(Thio, Freeze et al. 1999; G. Statham 2003)
Magneto-Kinetic Expansion (MKE)	2.2	1.0×10^{24}	10	67	(Slough 2001)

Z-PINCH FUSION PROPULSION

- Z-Pinch is a Magneto-Inertial Fusion (MIF) approach.
- To design a propulsion system, a concept mission and vehicle was designed.
  - Reference mission: to transport crew and cargo to Mars and back.
  - A vehicle from a previous nuclear fusion propulsion study* was used to provide a mass and many parameters in the design of a Z-Pinch propulsion system.
  - This study concentrated only on Z-Pinch propulsion concept and design.

* Magnetized Target Fusion (MTF) for the Human Outer Planet Exploration (HOPE) vehicle concept

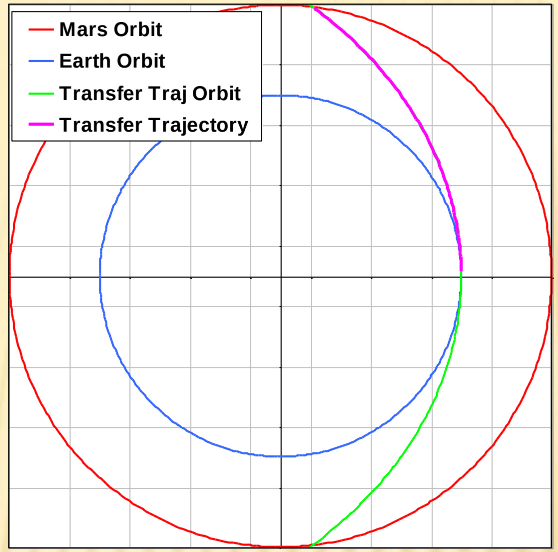
MISSION ANALYSIS

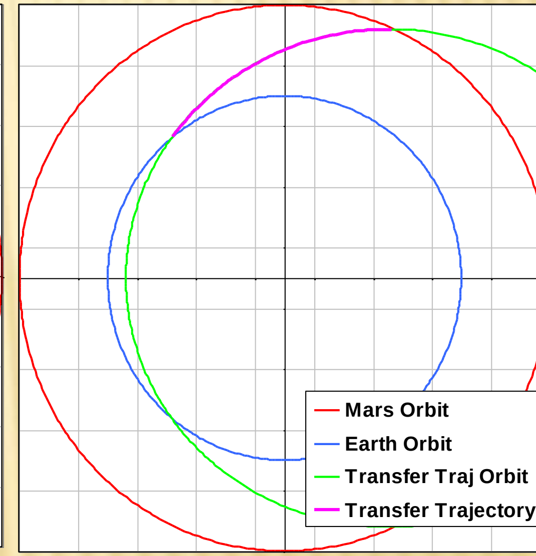
- Z-Pinch has milli-g thrust.
- I_{sp} is very high.
- Propellant mass reported doesn’t include escaping a planet’s gravity field.
- Simple orbit-to-orbit was modeled. Specific ephemeris data wasn’t used, except as noted on next page.

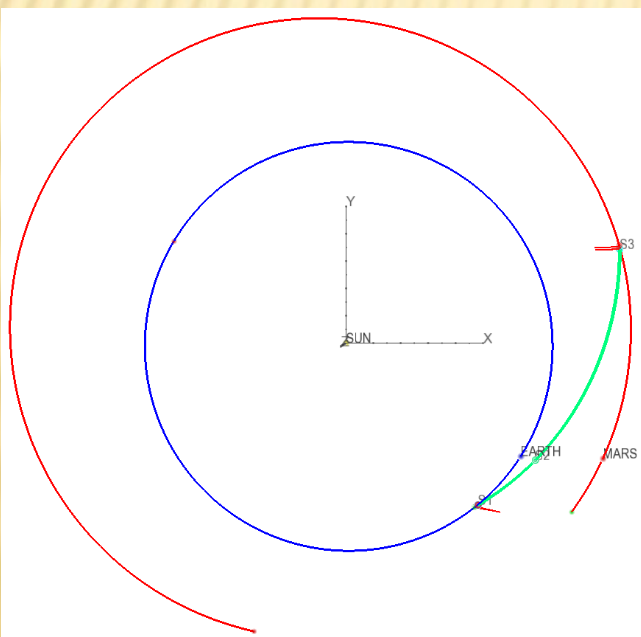
552 mT burn-out mass	Mars 90	Mars 30
Outbound Trip Time (days)	90.2	39.5
Return Trip Time (days)	87.4	33.1
Total Burn Time (days)	5.0	20.2
Propellant Burned (mT)	86.3	350.4
Equivalent ΔV (km/s)	27.5	93.2

MISSION TRAJECTORY

Outbound and return trajectories for a 90 day trip to Mars with a 1.5 day departure burn.



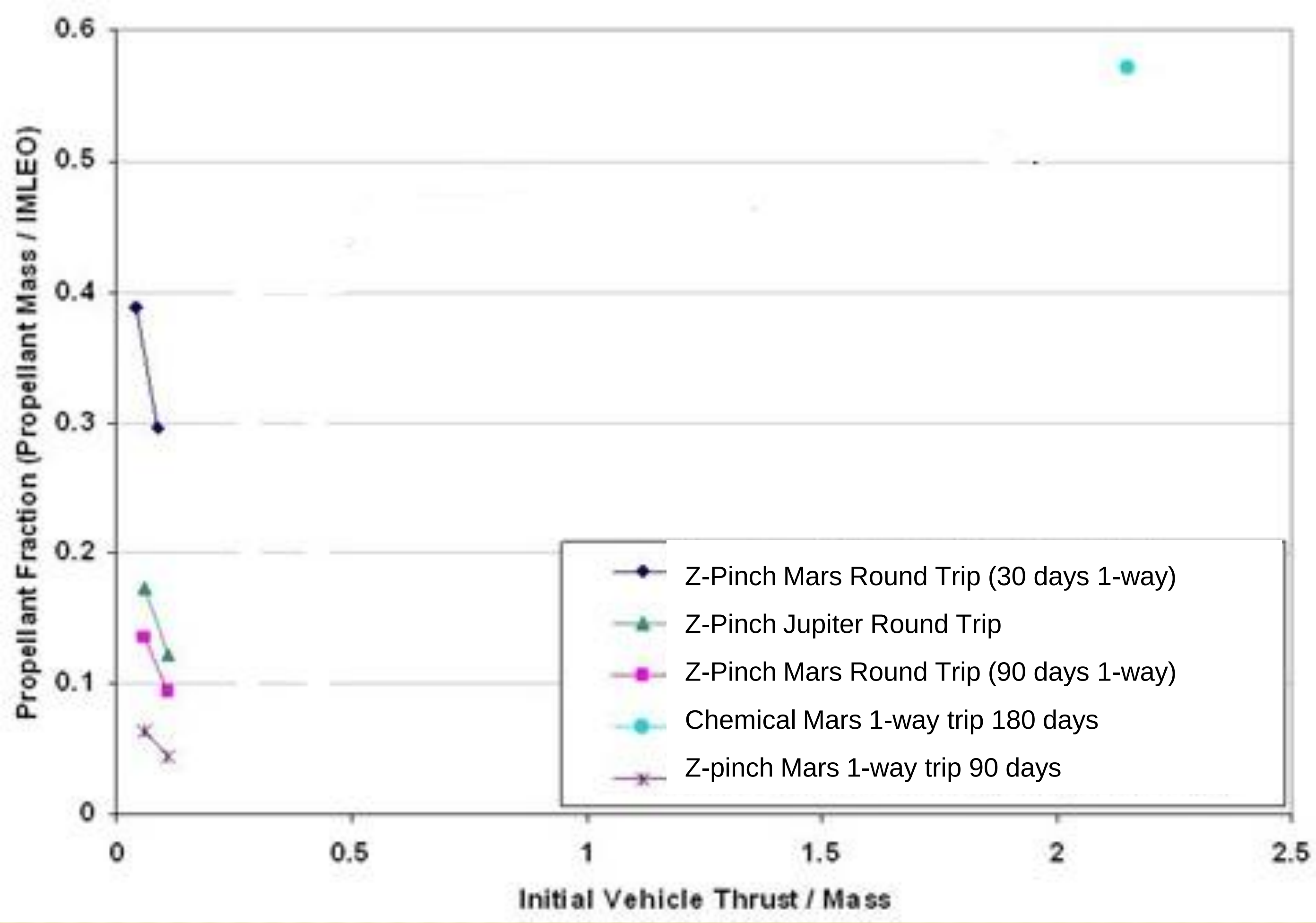




An optimal 90-day outbound trajectory to Mars departing Earth August 1, 2035.

In all trajectories, the burn time is so small compared to the coast time that these burns are not visible on the full trajectory plots.

MISSION DELTA V



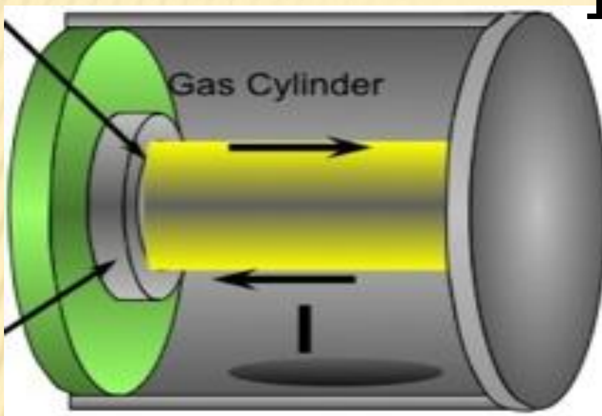
Z-PINCH MIF

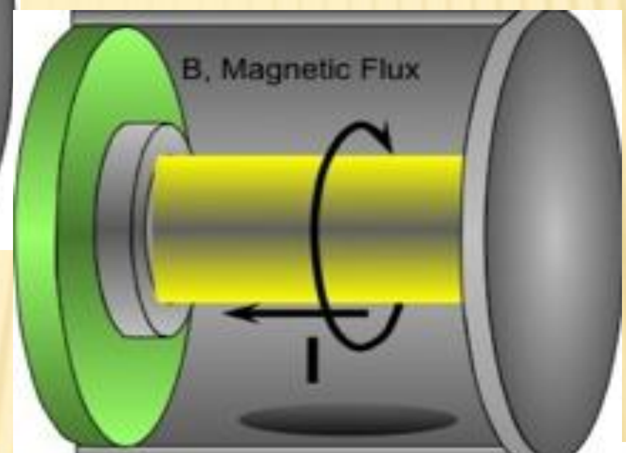
What is Z-Pinch Magneto-Inertial Fusion?

- A high current is sent through a column of gas.
- Cathode is along the Z-axis of column of gas.
- The magnetic field generated compresses the plasma to thermonuclear fusion conditions.
- There must be an anode or return path for electrons.
- Lots of energy is released as Z-pinch plasma expands via nuclear fusion reactions.

STAGES OF Z-PINCH FORMATION

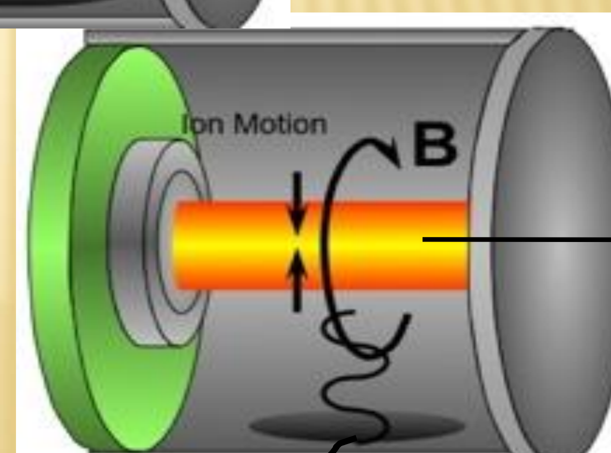
1) Gas Injection & Preionization





2) Initial Implosion

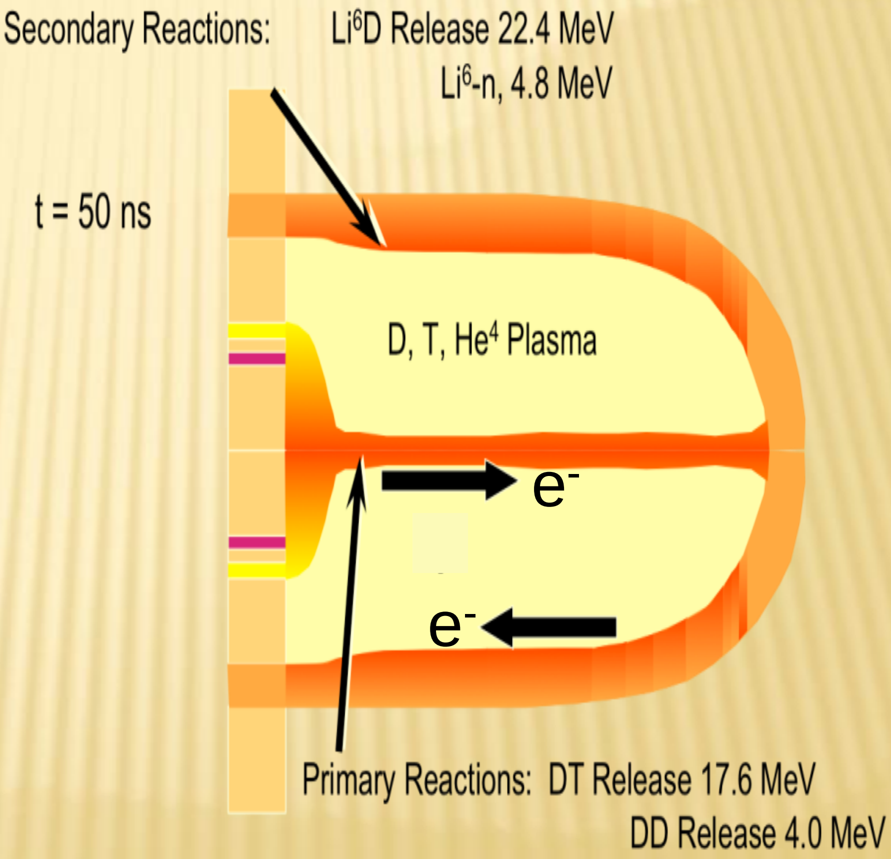
3) Implosion/stagnation



Z-PINCH MIF PROPULSION CONCEPT - 1

Z-Pinch Pulsed Propulsion

- A high current (Megampere scale) is pulsed into a column of Deuterium/Tritium (D-T) fuel injected along the Z-axis of a parabolic nozzle.
- The magnetic field generated by the high current compresses the plasma to thermonuclear fusion conditions.
- Simultaneously, Lithium^6 (Li^6) is injected through an annual nozzle.
  - D-T and Li^6 injection is focused in a conical manner so the mixture meets and the Li^6 liner can serve as a return path or anode to complete the circuit.
  - Li^6 is a secondary fuel and radiation shield/neutron-getter.



PRIMARY REACTIONS

$$D + T \rightarrow He^4\ (3.5\,MeV) + n\ (14.1\,MeV)$$

$$D + D \underset{50\%}{\rightarrow} T\ (1.01\,MeV) + p\ (3.02\,MeV)$$

$$D + D \underset{50\%}{\rightarrow} He^3\ (0.82\,MeV) + n\ (2.45\,MeV)$$

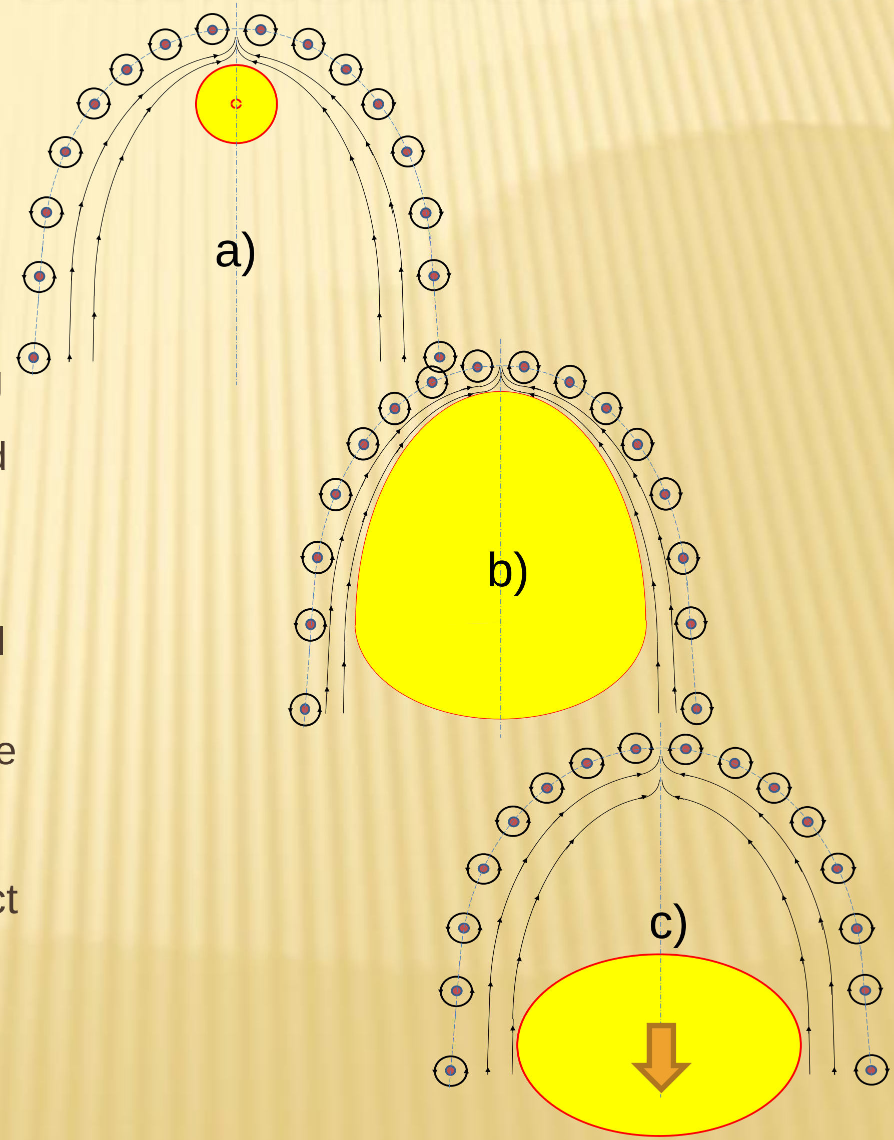
$$D + He^3 \rightarrow He^4\ (3.6\,MeV) + p\ (14.7\,MeV)$$

$$T + T \rightarrow He^4 + 2n + 11.3\,MeV$$

Z-PINCH MIF PROPULSION CONCEPT - 2

Z-Pinch Pulsed Propulsion (cont.)

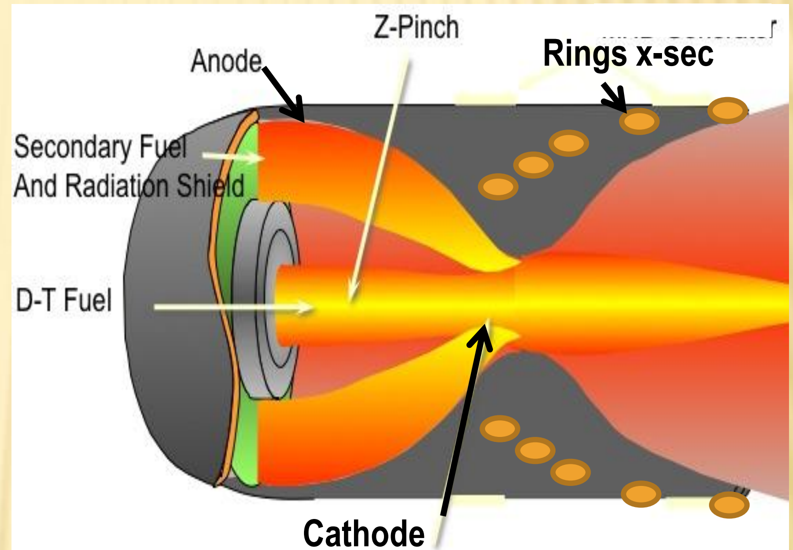
- The Z-Pinch reaction occurs within a parabolic magnetic nozzle composed of current-carrying coils with a superconductor that generates a magnetic field.
  - a) The highly conductive expanding plasma compresses the nozzle magnetic field, increasing its field strength.
  - b) Increasing magnetic pressure slows the plasma expansion transforming kinetic into potential energy.
  - c) Plasma is expelled, parallel to the nozzle axis, with useful thrust applied to the vehicle.
- Magnetic field pressure prevents contact between high temperature ionic plasma and the nozzle coils/material, but still imparts a force/thrust to the structure.



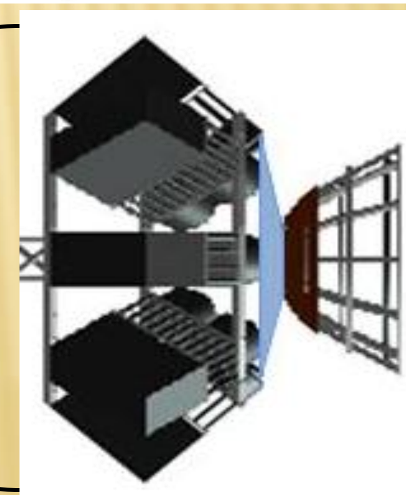
Z-PINCH MIF PROPULSION CONCEPT - 3

Z-Pinch Pulsed Propulsion (cont.)

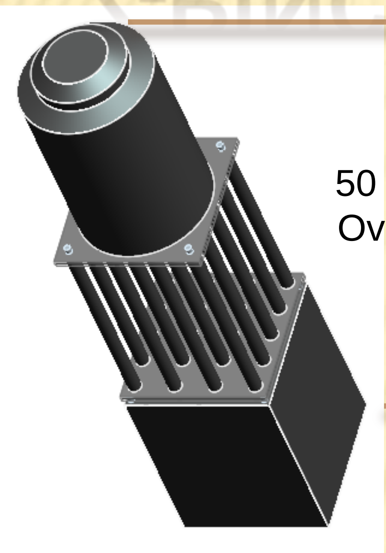
- Nozzle thrust coils also have a second conducting ring that supports the electrical current induced during plasma expansion.
- This current is used to recharge giant capacitor banks to enable delivery of the next current pulse.
- To create the conditions necessary for fusion, each capacitor discharge is applied to the fuel bolus in about 100 nanoseconds.
- Capacitors must have very low capacitance, for very rapid discharge at incredibly high voltage.
- Pulse process is repeated over small timescales (10 Hz).



Capacitor bank

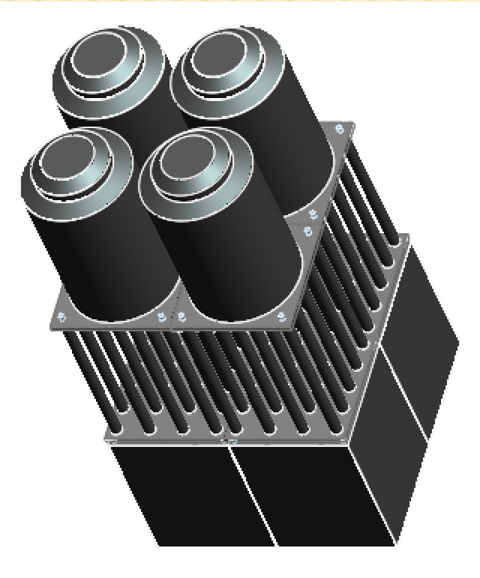


Z-PINCH DM2 ASSEMBLY CONCEPT

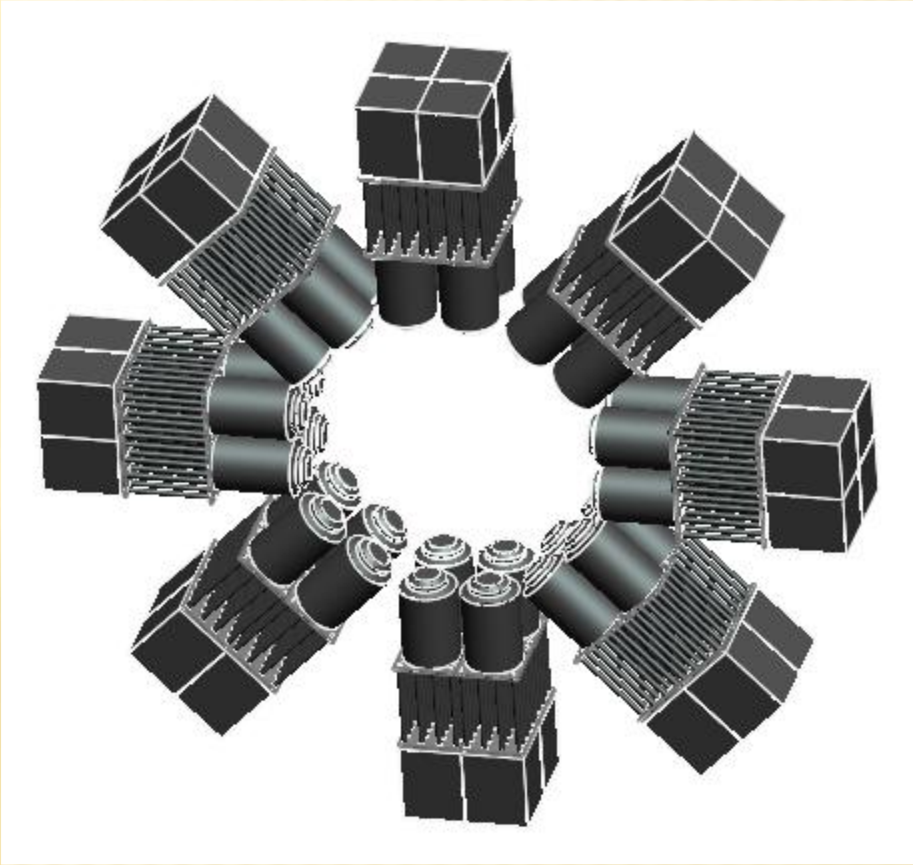


50 ft. (15.2 m)
Overall Height

Single DM2
Capacitor
Module



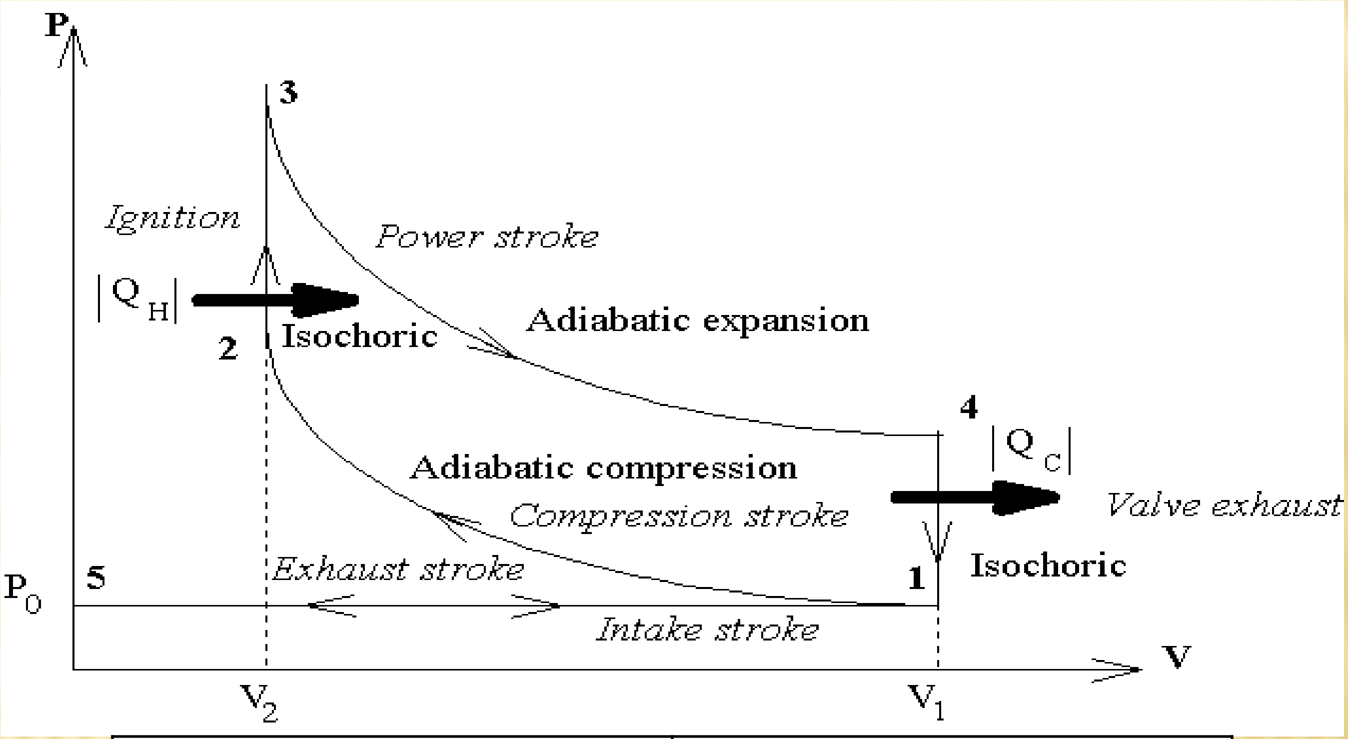
Four DM2 Modules



32 DM2 Modules

Charge transmission lines
not shown

OTTO CYCLE – MODELING ASSUMPTIONS

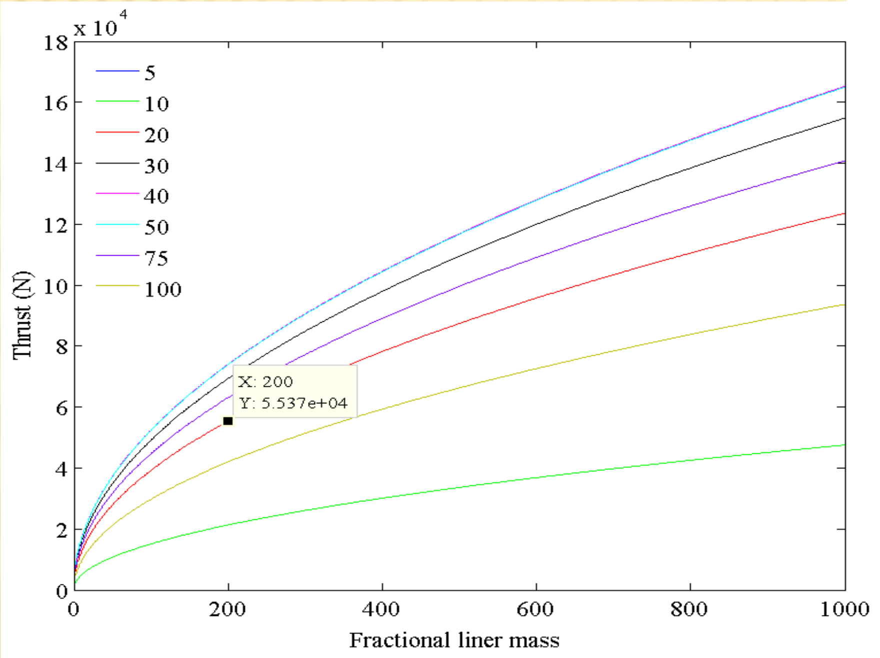


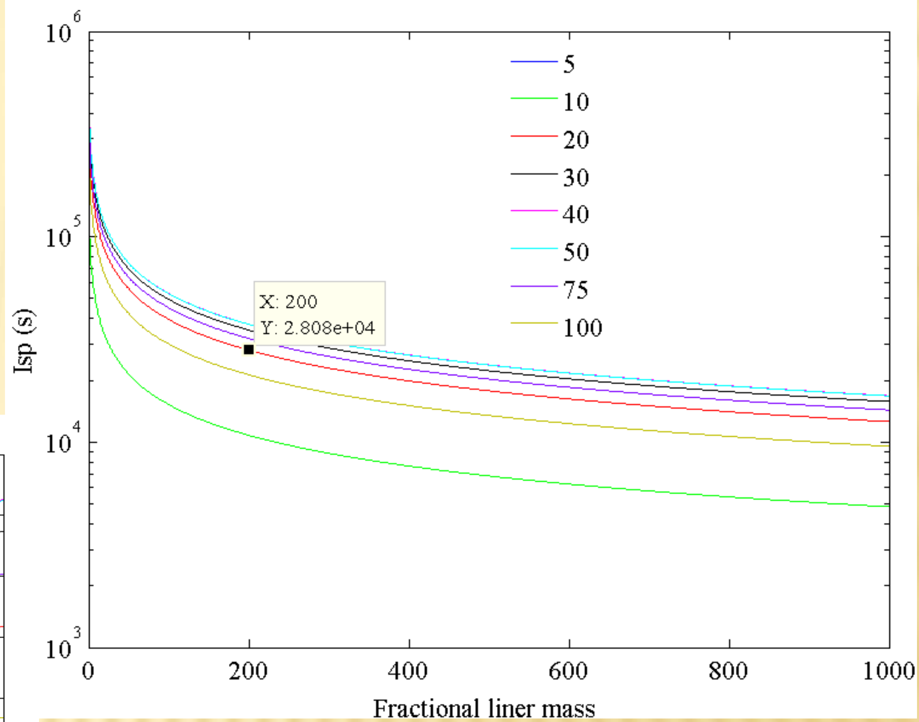
Pulse Frequency	10 Hz
Driver Energy Density	10 kJ/kg
Compression Ratio (R_1/R_2)	10
Initial DT Fuel Mass	100 mg
Lithium Liner	200 x m_{DT} (20 g)
Ignition Temperature	20 keV

THRUST & I_{SP} ESTIMATE

Pulse mass: 200 x m_{DT} or .02 kg
Initial Kinetic energy: 1 GJ
Useful impulse/pulse: 3812 N-sec

I_{sp}: 19436 sec





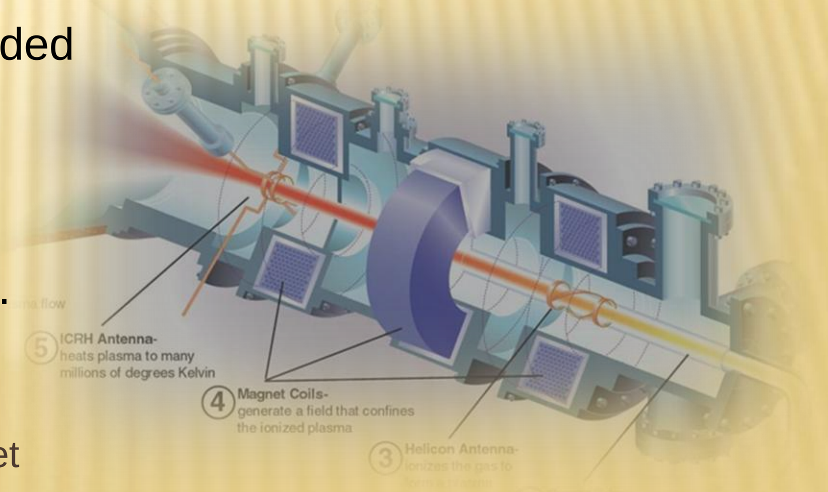
PARAMETER ASSUMPTIONS

Pulse Frequency	10 Hz
Driver Energy Density	10 kJ/kg
Compression Ratio	10
Initial DT Fuel Mass	100 mg
Ignition Temperature	20 keV

Z-PINCH FUSION MAGNETIC NOZZLE

The design of a magnetic nozzle to contain and direct the energy pulses of the fusion reaction is key.

- A simplified Z-Pinch fusion thermodynamic model developed parameters to characterize the propulsion system.
- The nozzle must withstand repeated high energy fusion reactions, extreme temperature and radiation.
- Magnetic nozzle design development has already begun with VASIMR*.
    - VASIMR engine is magnetically shielded and does not come into direct contact with plasma. Powerful superconducting electromagnets, employed to contain hot plasma, generate tesla-range magnetic fields.

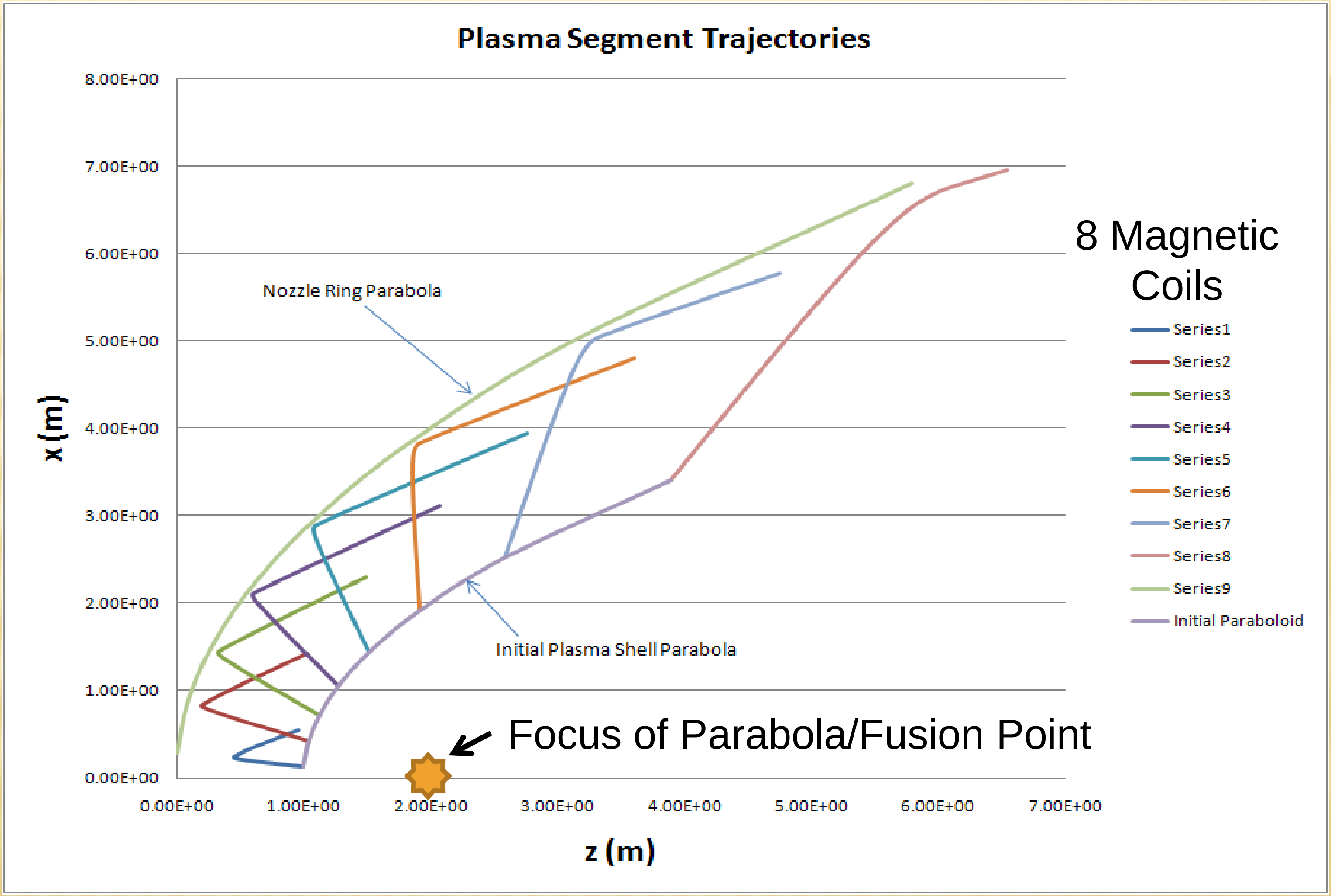


* Variable Specific Impulse Magnetoplasma Rocket

MAGNETIC NOZZLE PERFORMANCE MODEL

- Transforms a spherical explosion to a paraboloid expansion.
- Captures useful impulse late in the expansion.
- Flux compression and magnetic pressure are at a maximum.
- Assume the parabolic focus/fusion point is 2 m from the apex of the nozzle.
- The expanding plasma has a total mass of 0.02 kg and its initial kinetic energy is assumed to be 1 GJ (1×10^9 Joules).
- The resulting plasma trajectories defined the dimensions and the loads subjected to the magnetic nozzle.

NOZZLE DESIGN – PLASMA TRAJECTORIES



MAGNETIC NOZZLE COILS

- The Performance Nozzle Model determined the required magnetic field(s) to handle fusion pulses.
- Eight rings were required to provide a continuous parabolic-shaped magnetic nozzle.
- Each coil must have two separate conducting rings.
- A superconducting ring generates the initial seed magnetic field.
- The second conventional conducting ring supports the electrical current that is induced during plasma expansion.
- This current recharges the capacitor banks to enable delivery of the next current pulse.
- In addition to the two conductors there are cooling channels, structure, and neutron-protection features that must be incorporated in the design.

Z-PINCH THRUST COIL X-SECTION

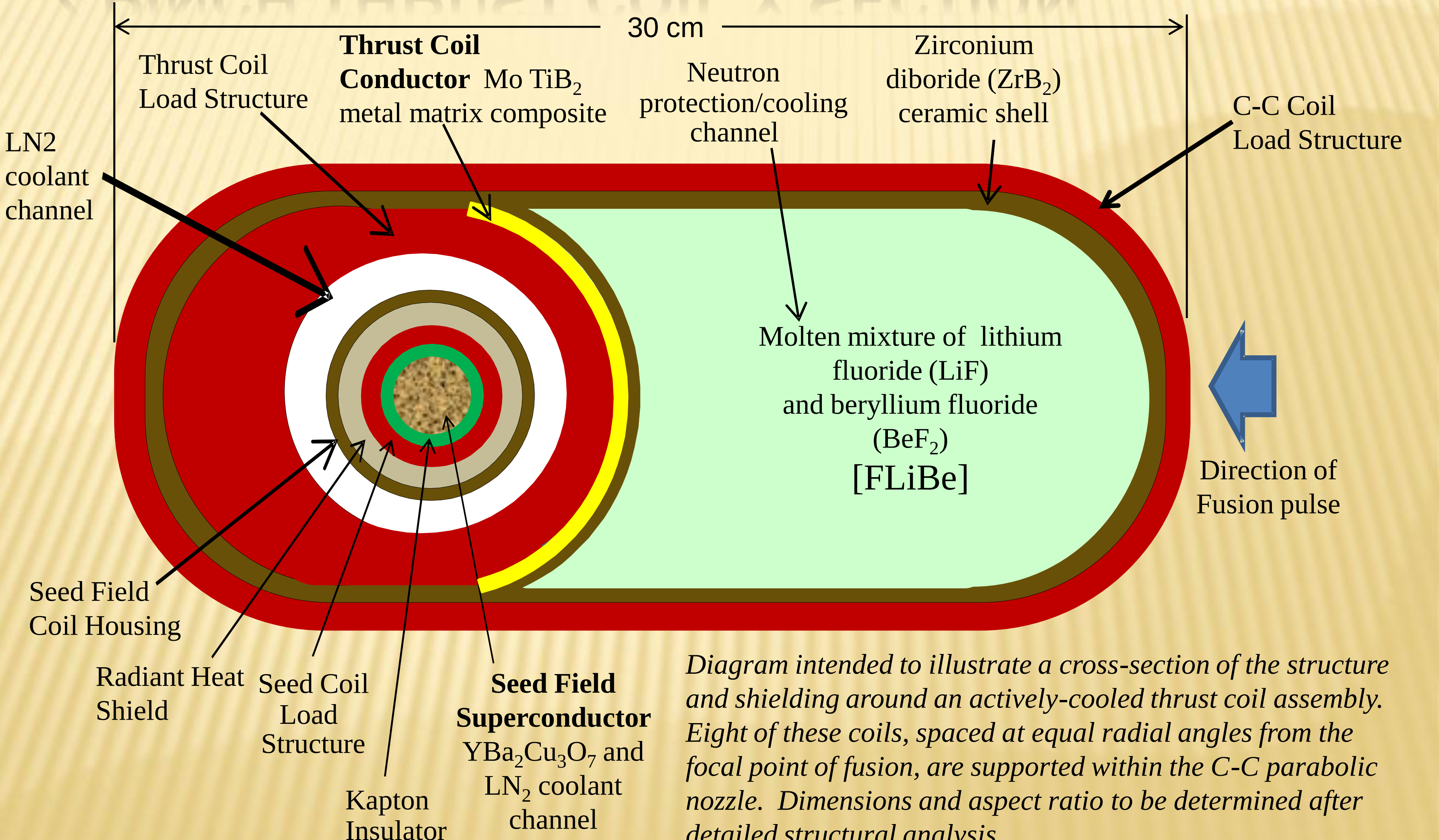
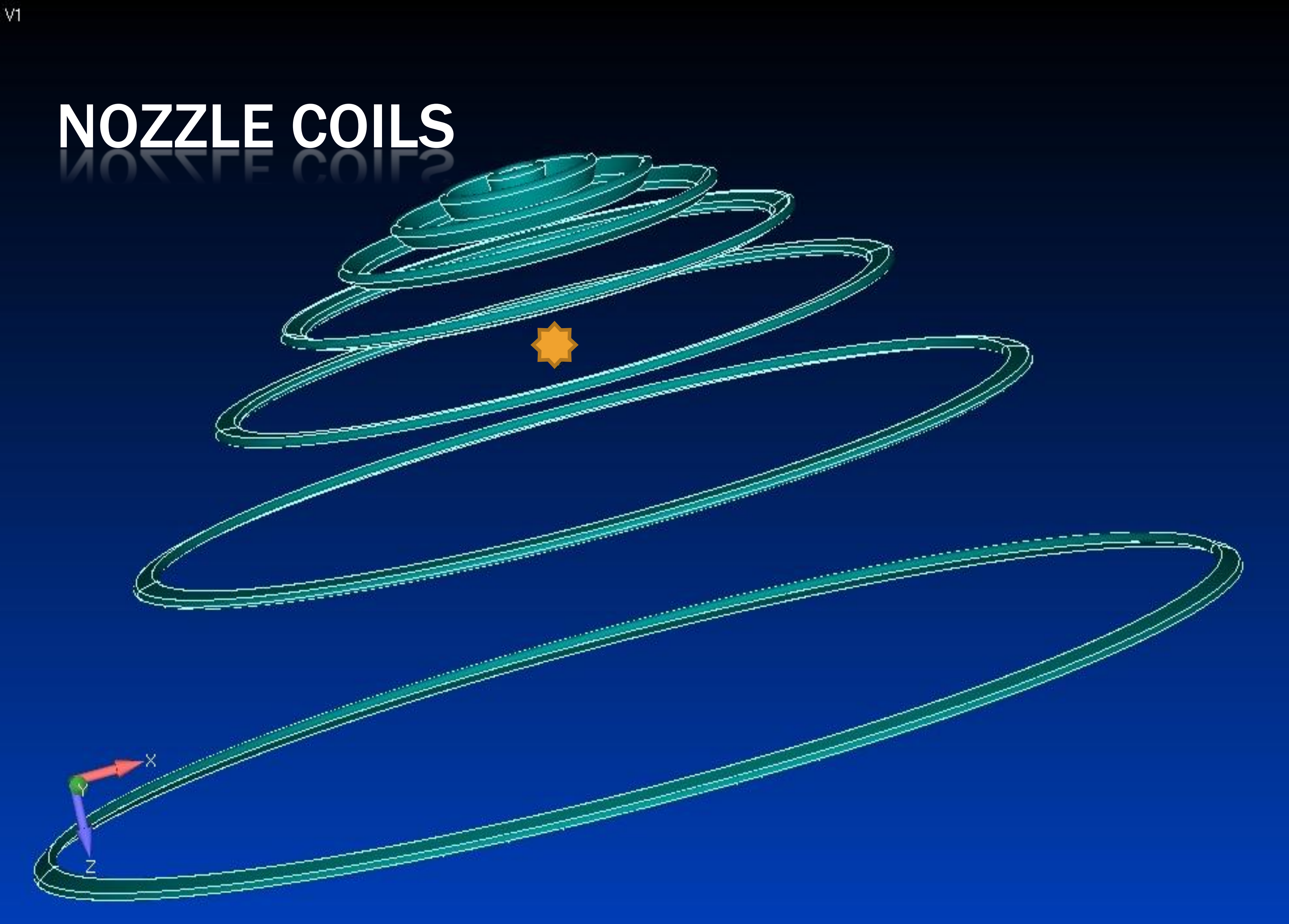


Diagram intended to illustrate a cross-section of the structure and shielding around an actively-cooled thrust coil assembly. Eight of these coils, spaced at equal radial angles from the focal point of fusion, are supported within the C-C parabolic nozzle. Dimensions and aspect ratio to be determined after detailed structural analysis.

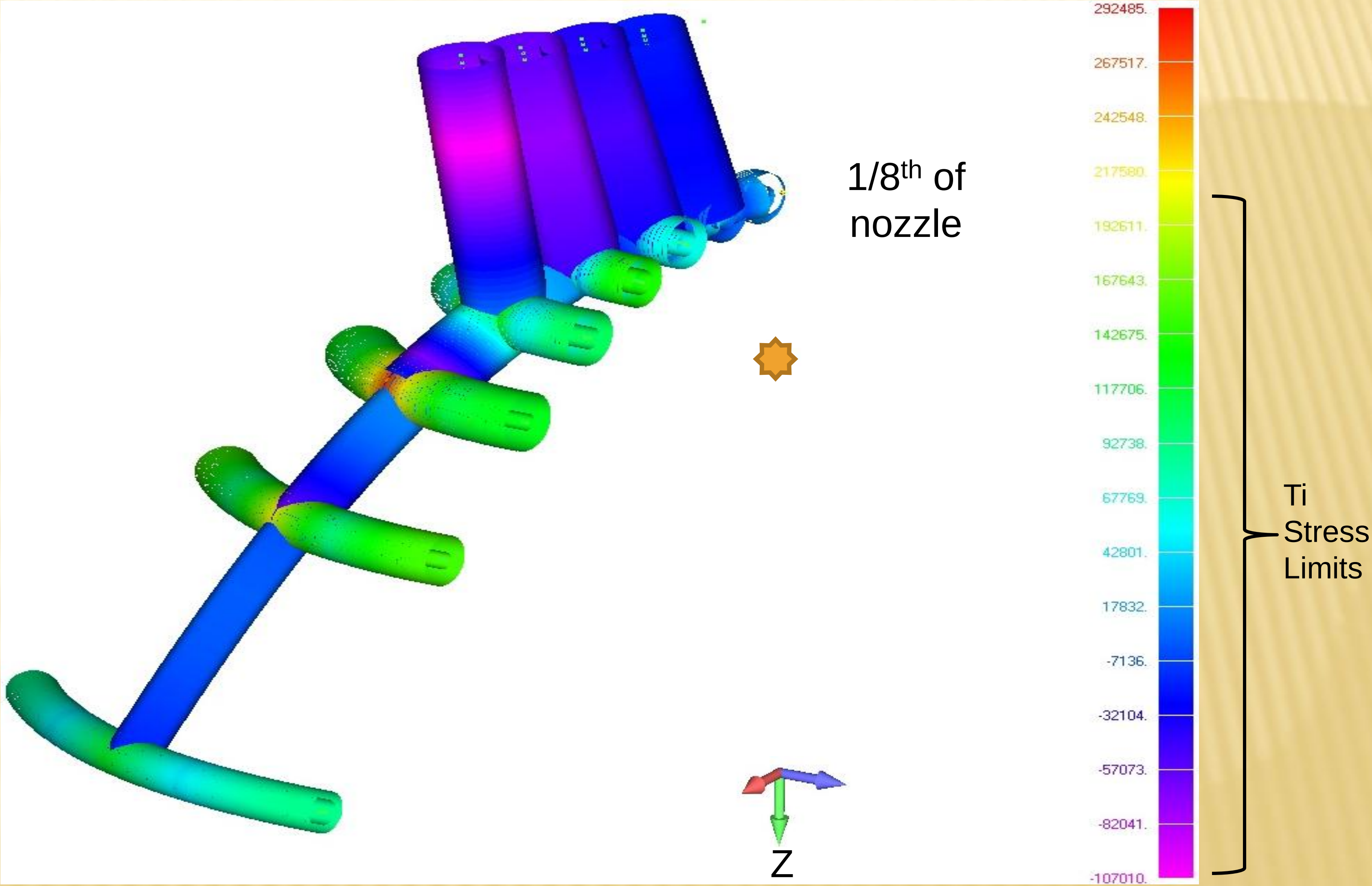
NOZZLE COILS



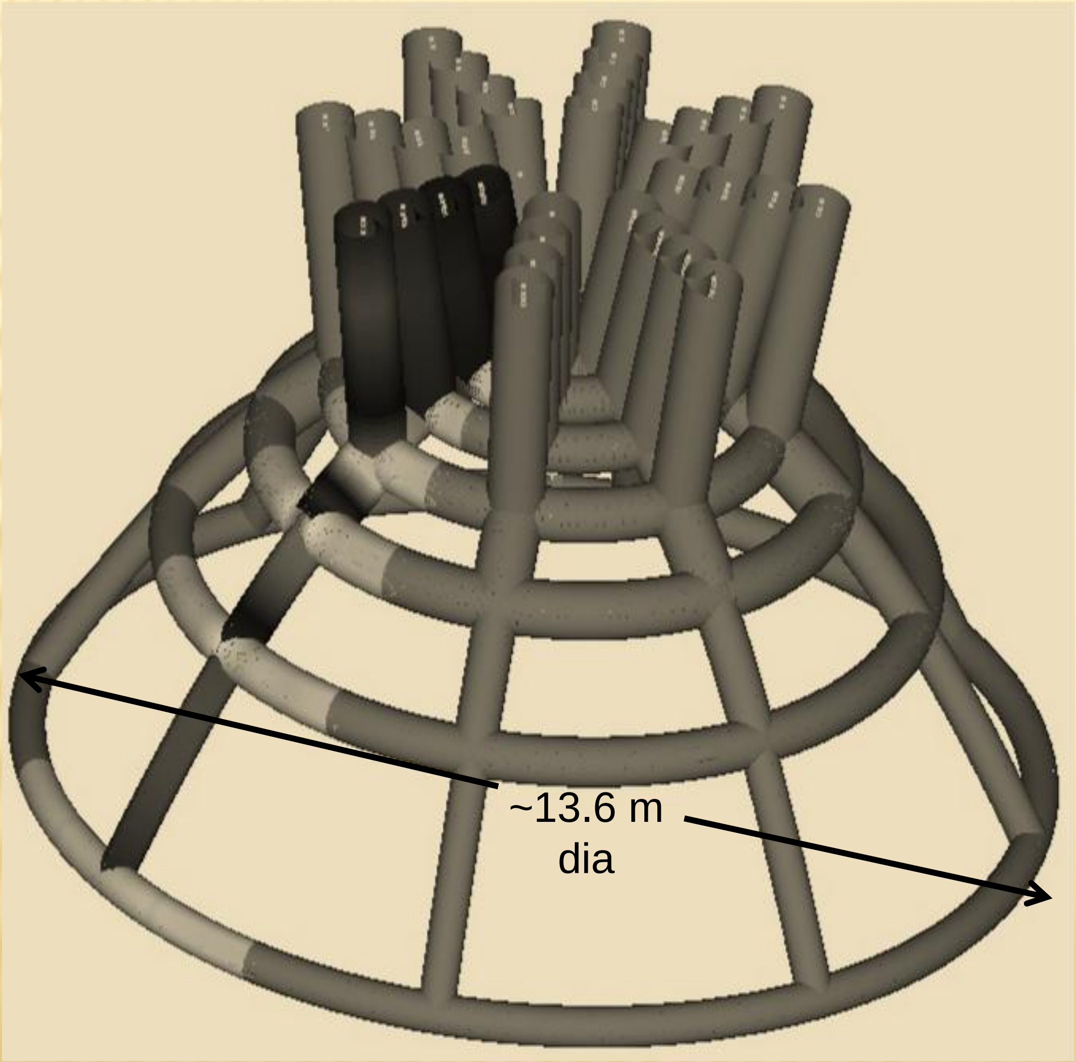
DATA TO BUILD FEM MODEL

Ring No.	Z (m) from parabolic origin	Ring Major Radius (m)	2πr (m)	# Nodes in 1/8 Model	# Nodes on ring	Max. Axial Force acting on ring (N)	Max. Radial Force/Linear Presure acting on ring (N/m)	Axial Force N/node	Radial Force N/node
1	9.64E-03	2.78E-01	1.747	7	48	8.39E+07	2.74E+06	1.75E+06	9.97E+04
2	8.90E-02	8.44E-01	5.303	19	144	5.49E+08	2.20E+07	3.81E+06	8.10E+05
3	2.61E-01	1.44E+00	9.048	25	192	1.38E+09	5.57E+07	7.19E+06	2.62E+06
4	5.56E-01	2.11E+00	13.258	37	288	1.93E+09	7.78E+07	6.70E+06	3.58E+06
5	1.04E+00	2.88E+00	18.096	49	384	1.72E+09	6.95E+07	4.48E+06	3.28E+06
6	1.82E+00	3.82E+00	24.002	61	480	1.03E+09	4.16E+07	2.15E+06	2.08E+06
7	3.19E+00	5.05E+00	31.730	91	720	4.05E+08	1.65E+07	5.63E+05	7.27E+05
8	5.79E+00	6.81E+00	42.789	109	864	1.02E+08	4.20E+06	1.18E+05	2.08E+05

FEM MODEL ANALYSIS



NOZZLE CONFIGURATION- FEM



• Thick-walled tubing was modeled to simulate fluid passages for coolant/FLiBe.

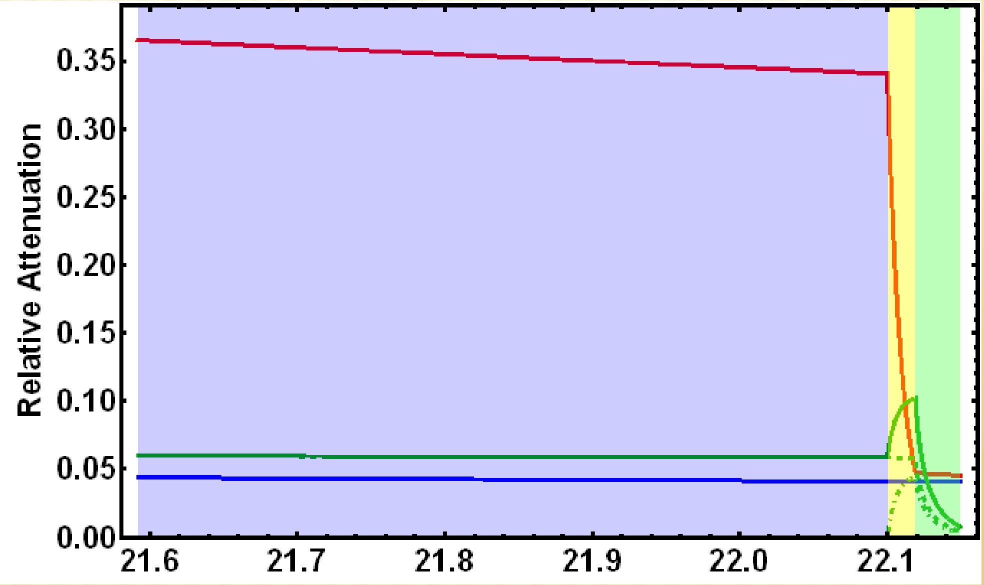
• Coils are embedded in 8 splines and supporting structural rings.

•Carbon Composite (C/C), (graphite epoxy, IM7/8552, >95% carbon) 3D high strength material.

•Struts extended to the vehicle truss structure to transfer the fusion pulse forces.

RADIATION PROTECTION

- The Li^6 fuel will absorb and carry away some neutrons and will slow down many more.
- A 3-layer neutron shield, 25 cm, will cap the magnetic nozzle.
- Lithium Hydride (LiH) slows/gets neutrons 50% better by mass than water MP 960 ° K.
- Boron carbide (B_4C) captures thermal neutrons.
- A thin layer of Tungsten (W) is needed to reduce the gamma rays.
- Beryllium shields behind the capacitor banks will also deflect gamma rays.

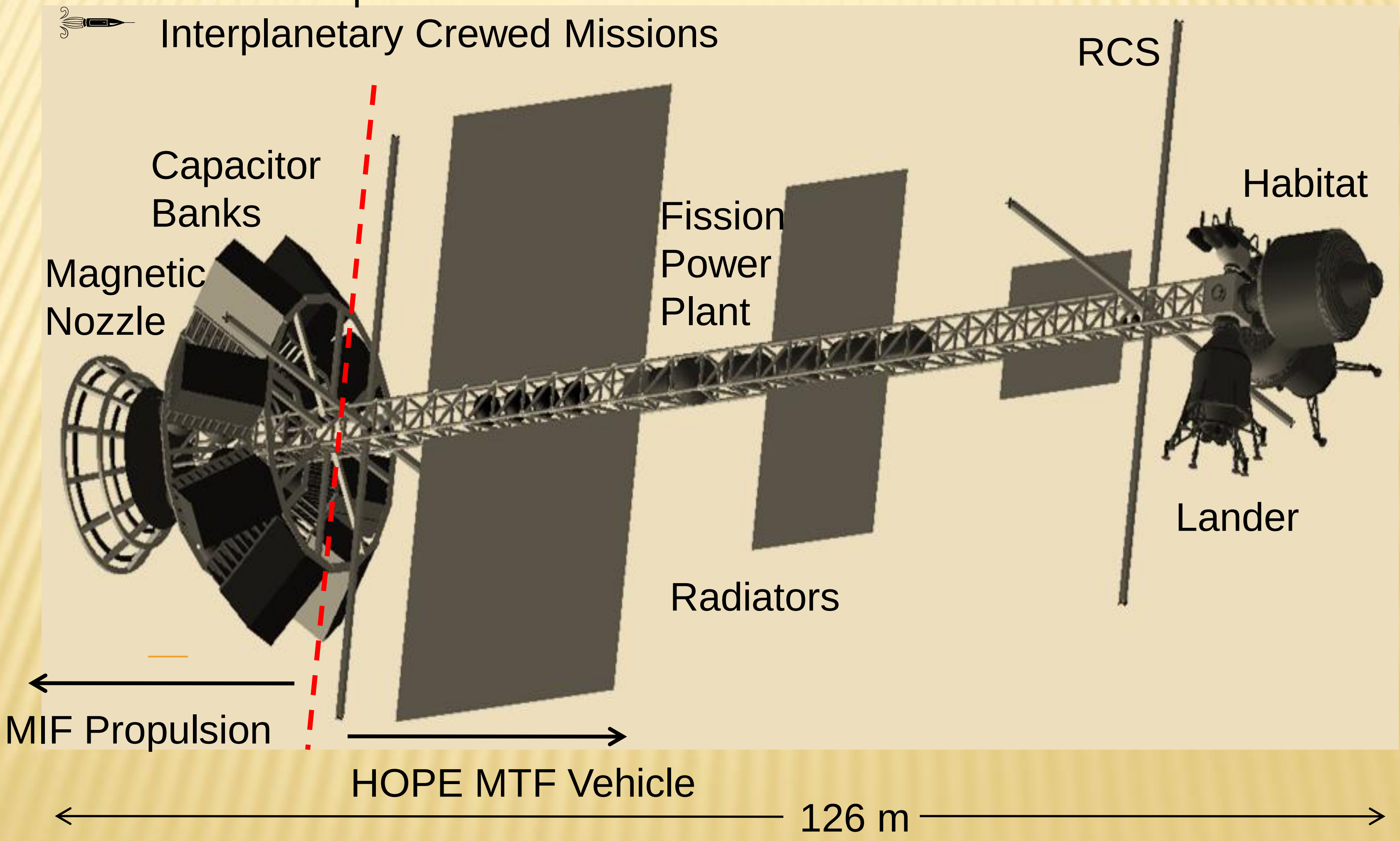


Radiation Shielding Thickness (cm) and Attenuation:

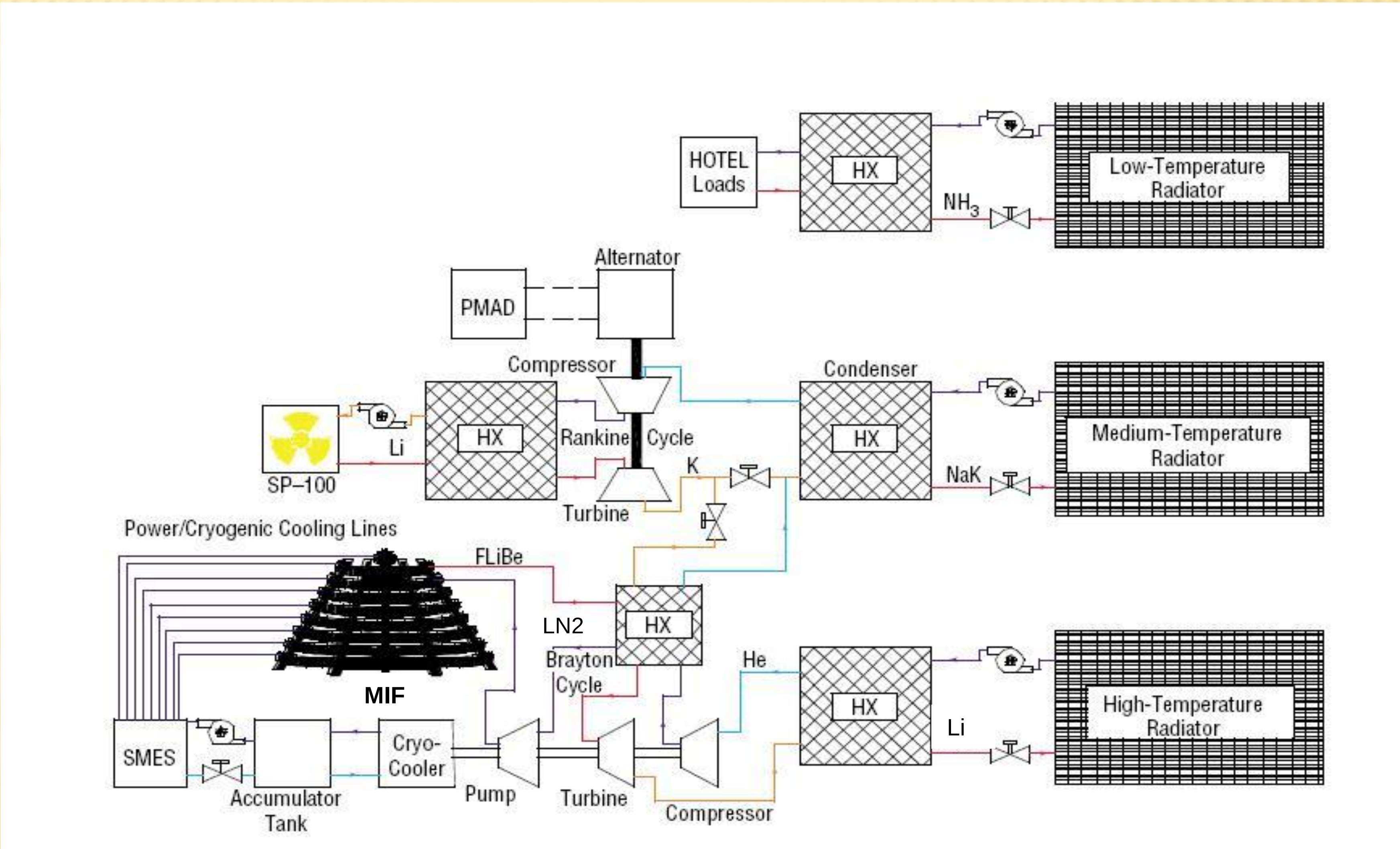
- Blue = 14.1 MeV neutrons.
- Red = Thermal neutrons.
- Green = Gamma rays.

VEHICLE CONCEPT

- Fusion Propulsion
- Interplanetary Crewed Missions



POWER, THERMAL, PROPULSION



MASS ESTIMATE

Subsystem	**Mass (kg)**
Payload – crew hab, lander, consumables, small transport, thermal, radiation protection and ECLS equipment for crew quarters.	150,000
Structures – Main truss, main propulsion tanks, secondary structure	36,500
Main Propulsion – MIF nozzle, coils, neutron/gamma shielding, FLiBe/LN2 coolant, capacitor/Marx generator recharge system	111,300
Main propulsion propellent – for 90-day Mars Round trip	83,000
Reaction Control System- tanks and propellent	3,500
Thermal Management – radiators, pumps, tanks, cryo coolers, thermal fluids	77,000
Power – fission reactor, radiation shield, and cooling loops	16,500
Avionics – control boxes, sensors.	1,700
Total Mass	479,500
30% Mass Growth Allowance	143,850
Total Mass (Best Estimate)	**623,350**

KEY TECHNOLOGY MATURITY

	TRL*
High Temperature Z-Pinch	4
Intense Electrical Pulse Power	4
Magneto-Hydrodynamic Electricity	5
Thermonuclear Equations of State	3
Dynamic Plasma Radiation Shielding	3
Advanced Structures	2
Reaction Containment	2

* Technology Readiness level

ACKNOWLEDGEMENTS

Z-Pinch Study Team:

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