FUSION PROPULSION Z-PINCH ENGINE CONCEPT

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ABSTRACT

Fusion-based nuclear propulsion has the potential to enable fast interplanetary transportation. Due to the great distances between the planets of our solar system and the harmful radiation environment of interplanetary space, high specific impulse (I_{sp}) propulsion in vehicles with high payload mass fractions must be developed to provide practical and safe vehicles for human spaceflight missions.

The Z-Pinch dense plasma focus method is a Magneto-Inertial Fusion (MIF) approach that may potentially lead to a small, low cost fusion reactor/engine assembly[1]. Recent advancements in experimental and theoretical understanding of this concept suggest favorable scaling of fusion power output yield [2]. The magnetic field resulting from the large current compresses the plasma to fusion conditions, and this process can be pulsed over short timescales (10^{-6} sec). This type of plasma formation is widely used in the field of Nuclear Weapons Effects testing in the defense industry, as well as in fusion energy research. A Decade Module 2 (DM2), ~500 KJ pulsed-power is coming to the RSA Aerophysics Lab managed by UAHuntsville in January, 2012.

A Z-Pinch propulsion concept was designed for a vehicle based on a previous fusion vehicle study called "Human Outer Planet Exploration" (HOPE), which used Magnetized Target Fusion (MTF) [3] propulsion. The reference mission is the transport of crew and cargo to Mars and back, with a reusable vehicle.

The analysis of the Z-Pinch MIF propulsion system concludes that a 40-fold increase of I_{sp} over chemical propulsion is predicted. An I_{sp} of 19,436 sec and thrust of 3812 N-sec/pulse, along with nearly doubling the predicted payload mass fraction, warrants further development of enabling technologies.

INTRODUCTION

Selected results of a study conducted in 2010 [4] by members of the Advanced Concepts Office (ACO) at MSFC are presented describing the conceptual design of a Z-Pinch Magneto-Inertial Fusion (MIF) fusion propulsion system. Figure 1 depicts a vehicle including all necessary systems for an integrated interplanetary spacecraft for human exploration. The basic design and mass of an earlier interplanetary vehicle conceived in a study called HOPE was used to develop the main propulsion engine utilizing the Z-Pinch MIF concept. This NASA study also offered recommendations for a Z-Pinch pulsed plasma propulsion technology development program that could be conducted at RSA utilizing a DM2 test article.

Z-Pinch physics and earlier fusion studies [5-7] were considered in the development of a simplified Z-Pinch fusion thermodynamic model to determine the quantity of plasma, plasma temperature, rate of expansion, and energy production to calculate parameters and characterize a propulsion system. The amount of nuclear fuel per pulse, mixture ratio of the Deuterium-Tritium (D-T) and Lithium-6/7 (Li^6) propellant, and assumptions about the efficiency of the engine facilitated the sizing of the propulsion system and resulted in an estimate of thrust and I_{sp} for the MIF Z-Pinch fusion propulsion engine of an interplanetary vehicle.

A magnetic nozzle is essential for fusion engines to contain and direct the nuclear by-products created in pulsed fusion propulsion. The nozzle must be robust to withstand the extreme stress, heat, and radiation. The configuration of fuel injection directs the D-T and Li^6 within the magnetic nozzle to create the Z-pinch reaction as well as complete an electrical circuit to allow some of the energy of the nuclear pulses to rapidly recharge the capacitors for the next power pulse. Li^6 also serves as a neutron shield with the reaction between neutrons and Li^6 producing additional Tritium and energy, adding fuel to the fusion reaction and boosting the energy output.
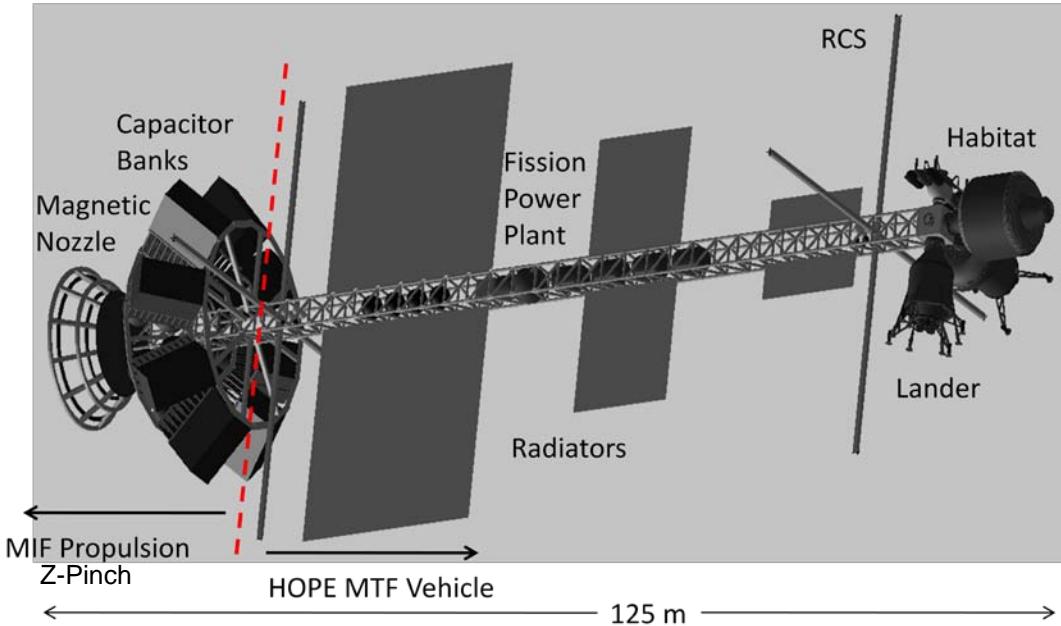

Figure 1 - Z-Pinch Vehicle Configuration

Trajectory analysis with the propulsion model was used to determine the duration of the propulsion burns, the amount of propellant expended, and the mixture ratio of the D-T and liner fuel to accomplish a particular mission. A number of missions, modeling variables, vehicle configurations, and design parameters were traded during the previously mentioned NASA studies; however, this paper concentrates on the conceptual Z-Pinch MIF nuclear engine of the proposed vehicle. An outline of the mission and vehicle configuration is offered to provide a framework for the propulsion design.

RESULTS AND DISCUSSION

The approach investigated in this study involves the use of a confinement scheme known as a Z-Pinch, which falls under the MIF regime. The Z-Pinch's basic function is to manage and run very large currents (Megampere scale) through plasma over short timescales (10^{-6} sec). The magnetic field resulting from the large current then compresses the plasma to fusion conditions. For a fusion propulsion system, the Z-Pinch is formed using an annular nozzle with D-T fuel injected through the innermost nozzle and Li^6 introduced through a cylindrical outer nozzle like a "shower curtain." The Li^6 propellant injection is focused in a conical manner, so that the D-T fuel and Li^6 mixture meet at a specific point that acts as a cathode. Li^6 will serve as a current return path to complete the circuit, as shown in two different graphical representations in Figures 2 and 3.

The Li^6 propellant becomes a nozzle "liner" and serves as a neutron "getter," as well as the current return path. The advantage of this configuration is the reaction of Li^6 and high energy neutrons produces additional Tritium fuel and energetic by-products that boost the energy output. Through careful introduction and mixture ratio of the injected D-T fuel and Li^6 propellant, the Z-Pinch reaction via MIF fusion can produce very high specific impulse by means of rapid exit velocity.

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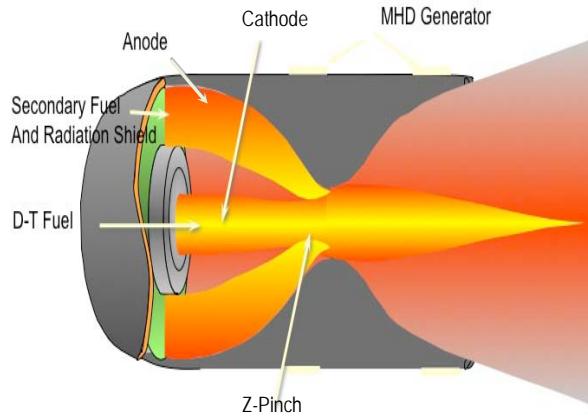
Figure 2 – Z-Pinch cathode runs axially down center   Figure 3 – Li[6] liner provides anode return path
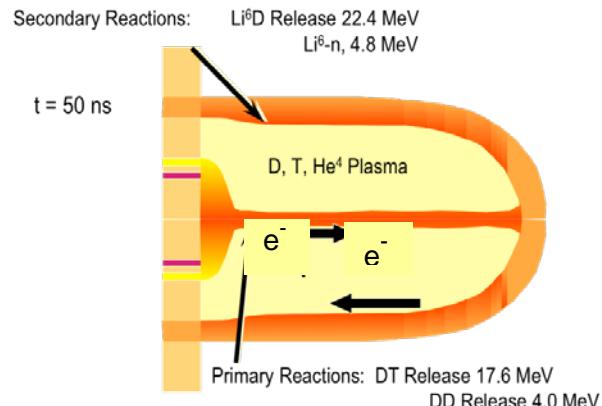
Analysis of fusion plasmas and their dynamic Magneto-Hydrodynamic (MHD) flows, as well as the fusion reactions themselves, necessitate the formulation of simple models and approximations to facilitate understanding. An approximation is made to develop a qualitative understanding of multiple fusion ignition processes. This is similar to the air-standard analysis of an internal-combustion engine, also known as an Otto engine. The Otto Cycle is shown in Figure 4.
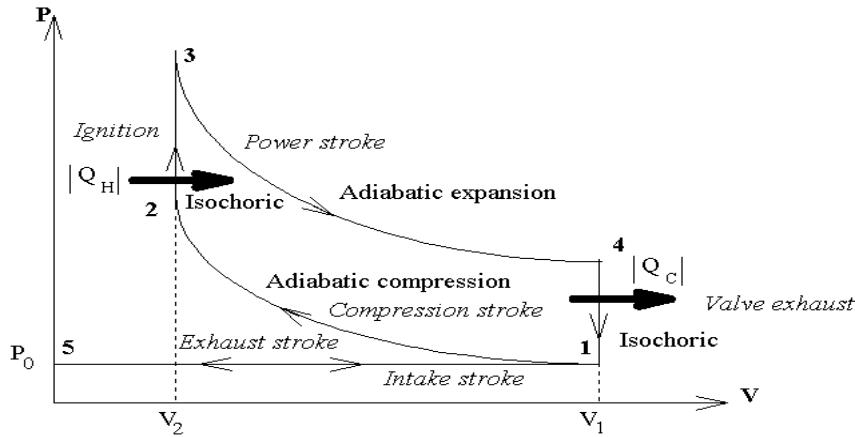

Figure 4 – Otto Cycle

There are several assumptions made about the molecular reactions and parameters in the analysis. The Li[6] is assumed to act as an inert element in the model, not reacting with the D-T fuel, only adding mass to the exhaust without adding further energy. Although Li[6] secondary reactions are expected, this makes the calculation a more conservative estimate. Parameter assumptions are shown in Table I.

Thrust and I_{sp} as a function of fractional liner mass over D-T fuel, were calculated with Table I values, yielding a recommended design point of 38 kN thrust and I_{sp} ~19,436 sec per pulse.

$$D + T \rightarrow He^4 \, (3.5 \, \mathrm{MeV}) + n \, (14.1 \, \mathrm{MeV})$$
$$D + D \underset{50\%}{\rightarrow} T \, (1.01 \, \mathrm{MeV}) + p \, (3.02 \, \mathrm{MeV})$$
$$D + D \underset{50\%}{\rightarrow} He^3 \, (0.82 \, \mathrm{MeV}) + n \, (2.45 \, \mathrm{MeV})$$
$$D + He^3 \rightarrow He^4 \, (3.6 \, \mathrm{MeV}) + p \, (14.7 \, \mathrm{MeV})$$
$$T + T \rightarrow He^4 + 2n + 11.3 \, \mathrm{MeV}$$
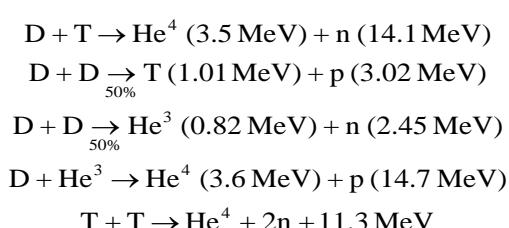
Pulse Frequency	10 Hz
Driver Energy Density	10 kJ/kg
Compression Ratio	10
Initial DT Fuel Mass	100 mg
Ignition Temperature	20 keV

Table I – Molecular Reactions & Parameter Assumptions

MAIN PROPULSION CONCEPT

After the energy is released during nuclear fusion, a magnetic nozzle converts the released energy into a useful vehicle impulse. The components of this magnetic nozzle are a series of 8 current-carrying rings. Each of the 8 ring assemblies that comprise the nozzle is actually composed of 2separate conducting rings.

Superconducting
Seed-Field Coil

Normally-Conducting
Thrust Coil
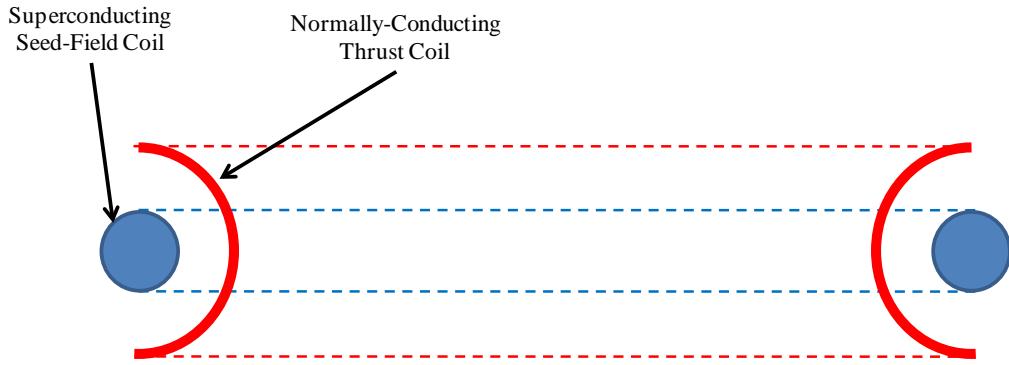
Figure 5 – Cross-section of coils in each ring assembly

These rings are positioned to form a parabolic nozzle focused at the point of fusion. As a result, an electrical current passes around each ring and results in a magnetic field as illustrated in Figure 6, which depicts the entire nozzle in cross-section.

After each fusion event, the plasma is hot and its shell is rapidly expanding. The plasma then begins to compress the magnetic flux into a smaller annular region between the plasma and the rings. As the magnetic flux is compressed, the field strength and the magnetic pressure on the expanding plasma shell prevents the plasma from contacting the rings. An equal and opposite force, much of it axially upwards along the main axis of the nozzle and the vehicle, transfers the kinetic energy of the plasma pulse to propel the vehicle.

Parabola
Focus/Fusion
Point

Magnetic Field Lines
Compressed by
Plasma Expansion
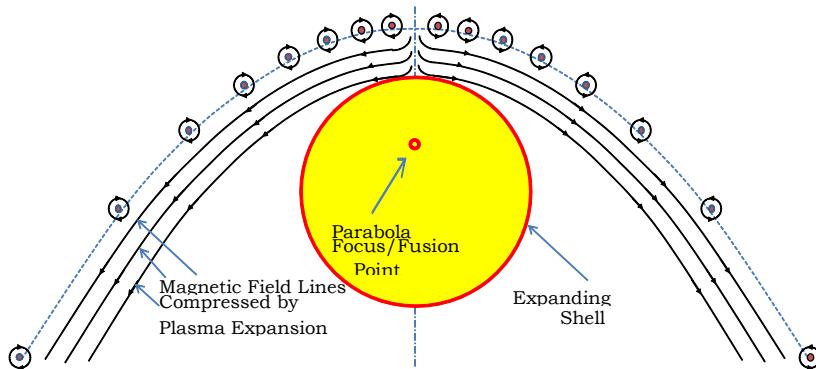
Expanding
Shell

Figure 6 – Magnetic nozzle in cross-section and expanding plasma

In each of the 8 ring assemblies there is a central superconducting coil that generates the initial seed magnetic field. Before fusion takes place, a magnetic field fills the volume of the nozzle. This coil is a high-temperature superconducting mesh immersed in liquid nitrogen (LN2) coolant. A yttrium-based superconductor ($YBa_2Cu_3O_7$) is proposed that has a transition temperature of 92 K, which can be maintained by LN2 at 77 K. The second conducting ring, the "thrust coil," supports the electrical current that is induced during plasma expansion. A metal composite of molybdenum in a matrix of titanium

diboride with very low resistivity would offer good electrical conduction and strength properties at high temperature.

Fluorine-Lithium-Beryllium (FLiBe) is proposed as the main thermal coolant and would flow through channels inside the ring assemblies, as well as through all the Carbon-Carbon (C-C) structure supporting the coils and comprising the nozzle and thrust struts. This fluid is suggested for the dual purpose of heat removal and capturing gamma rays and neutrons. Eight ring assemblies, spaced at equal radial angles from the focal point of fusion, are supported within the C-C parabolic nozzle. The shape and configuration of a ring assembly, shown in cross-section in Figure 7, would be angled toward the focus of the fusion pulses to allow the FLiBe to protect the magnetic conductor coils from neutrons. This radiation protection would be in addition to the Li[6] "liner" which is expected to absorb high energy neutrons and will slow down many more.
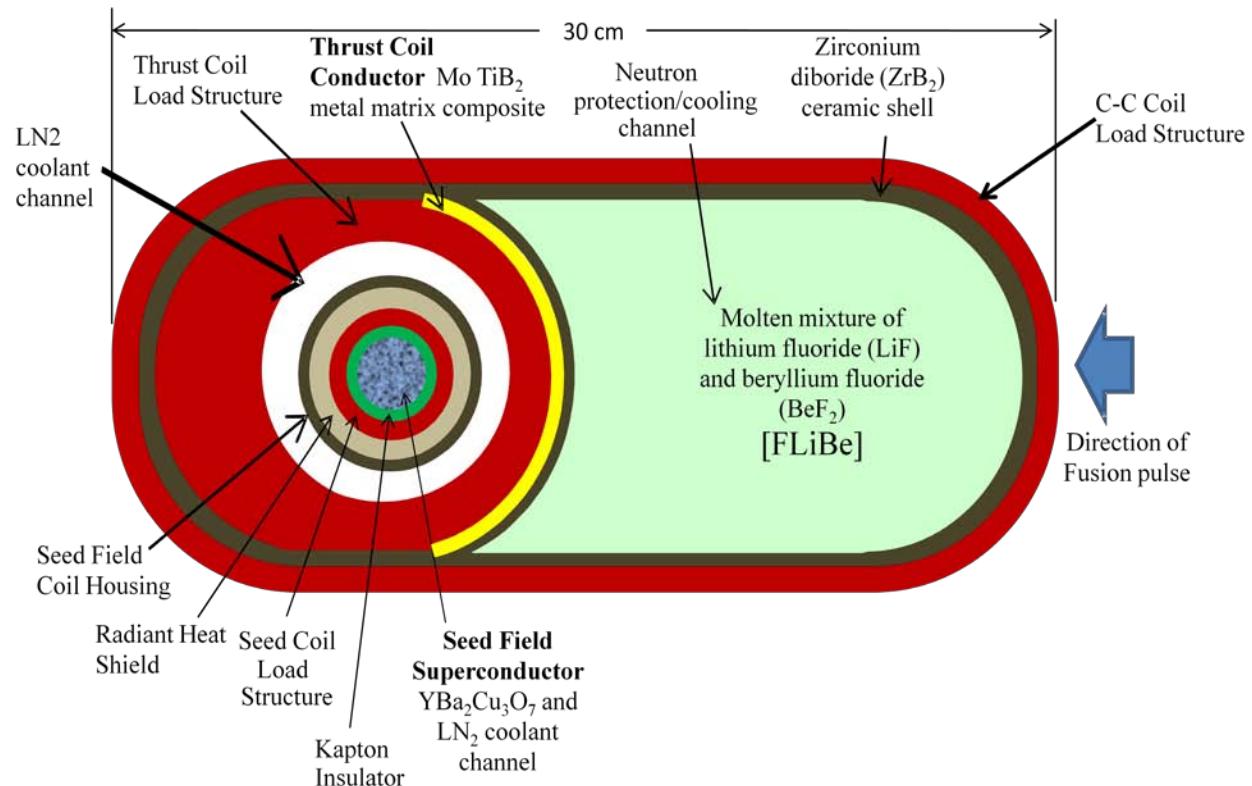

Figure 7 - Cross-section of the structure and shielding around an actively-cooled ring assembly. Dimensions and aspect ratio to be determined after detailed structural analysis.

Given that the rings are arranged in this shape, the plasma radiating outwards from the focus of the parabolic nozzle will be directed out of the nozzle, parallel to the axis – no matter where it strikes. After the plasma exits, the magnetic field returns to its original configuration. During this entire process, of plasma expansion and expulsion, the magnetic field acts in the manner of a spring. The magnetic fields are first compressed, and then they expand back to the original configuration – with useful thrust being applied to the vehicle via the thrust coils embedded in the structural C-C nozzle. There are additional structural, cooling, radiation and neutron shielding components incorporated in the design of the magnetic nozzle along with the ring assemblies.

For modeling purposes, the plasma expansion shell is divided into 8 discrete segments. Each is positioned at equal spherical angles from the fusion point, which is by design at the focus of the parabolic nozzle. Figure 8 shows the actual plasma ejection trajectories modeled.

In summary, 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). Useful thrust to the vehicle per pulse = 3812 N-seconds and at 10 Hz (10 pulses/sec) I_{sp} = 19,436 seconds. This was used to provide the loads for structural analysis of the magnetic nozzle and ring assemblies.
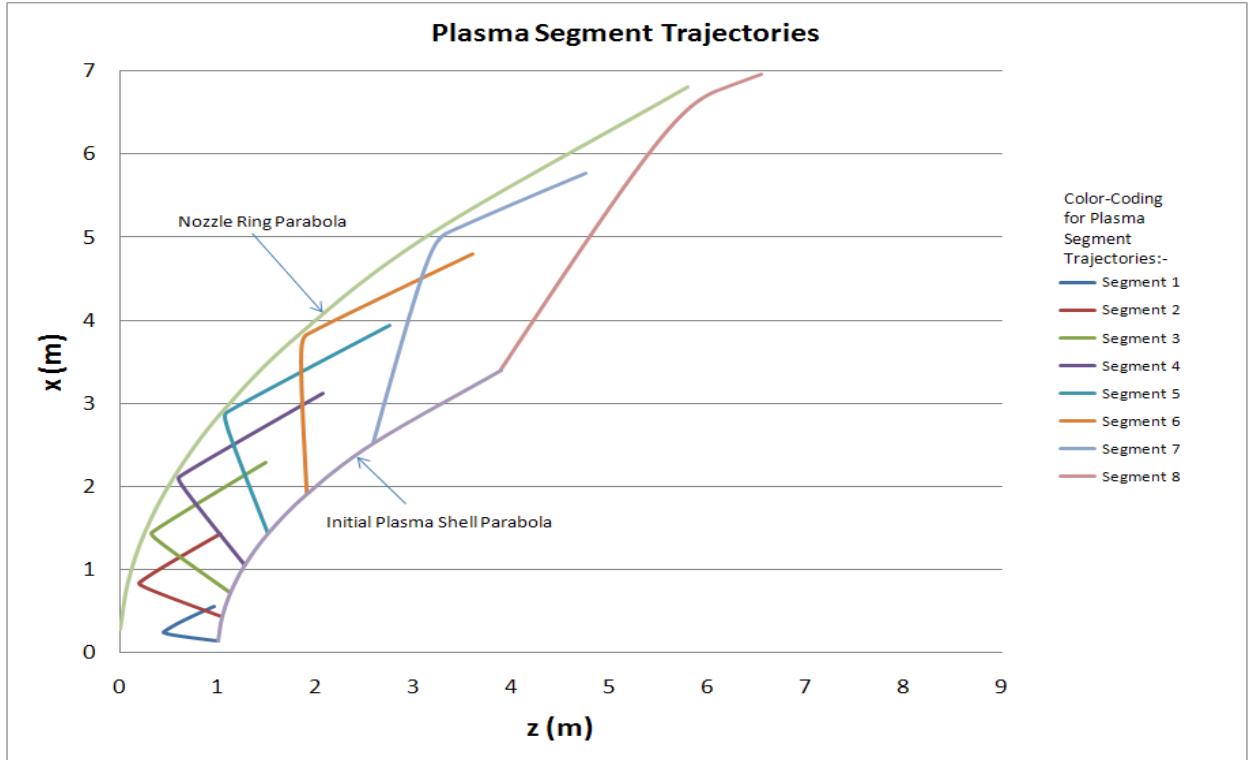

Figure 8 – Plasma trajectories exiting nozzle over 15 microseconds

Z-PINCH ENERGY REGENERATION / DISCHARGE SYSTEM

A large amount of energy must be applied to the DT fuel bolus over a period of just around 100ns to create the conditions necessary for fusion. To do this, capacitor banks with very low capacitance must be used so that the discharge will be rapid. The banks must be charged to a very high voltage for them to store enough energy. After discharging to create the Z-Pinch, these capacitor banks must be recharged for the next pulse. During each fusion pulse, the current induced in the thrust coils is used to recharge the capacitors. The Z-Pinch regeneration/discharge subsystem consists of circuitry (capacitors, cables, switches, etc.) required to charge and discharge the capacitors.

The thermodynamic model used to size the fusion portion of the propulsion system estimates the Z-Pinch gain at 3: meaning that the amount of energy released by the fusion reaction is 3 times the amount of energy required for ignition. Assuming each pulse generates 1GJ, 333 MJ must be discharged into the DT fuel pulse in 100ns to initiate fusion. The capacitor charge efficiency is assumed to be 80%, so 416 × 10^{-6} J must be available in the capacitor bank.

Even though the capacitors must discharge over a 100ns period, they have a longer period to recharge, assuming a 10 Hz pulse frequency for the propulsion system. Capacitors may be charged in parallel and discharged in series, so a circuit may be devised that allows a large bank of capacitors to be charged over several microseconds and discharged much more quickly with very little loss. This circuit is known as a Marx Generator and, for this application, individual capacitors are sized by traditional physics-based methods according to required voltage and capacitance. The plasma switches and diodes are not sufficiently well characterized to size with a mass estimating relation, so they are sized as 12% of the

capacitor mass. Eight sections of capacitors are arranged radially in a ring surrounding the axis of the magnetic nozzle.

Diodes prevent ringing between the capacitive and inductive portions of the circuit, while the plasma switches complete the series discharge circuit as for a typical Marx Generator, which is shown as a schematic in Figure 9.
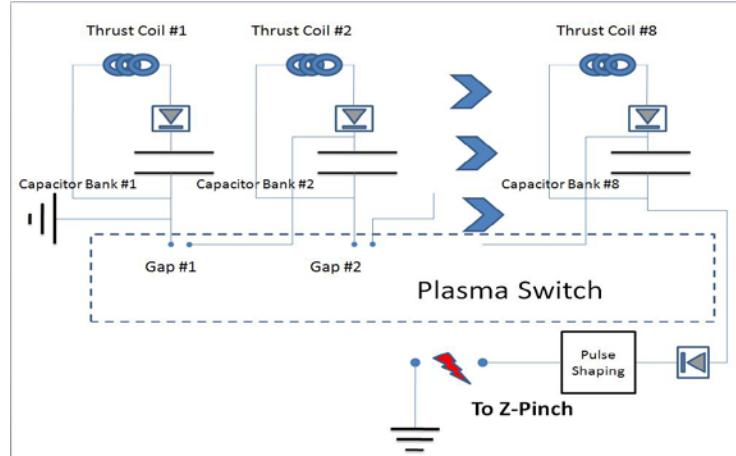

Figure 9 - Basic schematic of the charge/discharge system.

THERMAL SYSTEM

The thermal subsystem, devised during the HOPE study is comprised of three separate heat rejection systems, which are described briefly in the following list and Figure 10:

- A low-temperature radiator system for the avionics and crew systems
- A medium-temperature (800 K) radiator for the fission power plant
- A high-temperature (1250 K) radiator for the propulsion system waste heat
- A cryo-fluid management system utilizing He and NaK to cool LN_2 and FLiBe that reject heat from the Superconducting Magnetic Energy Storage (SMES) and magnetic nozzle ring assemblies
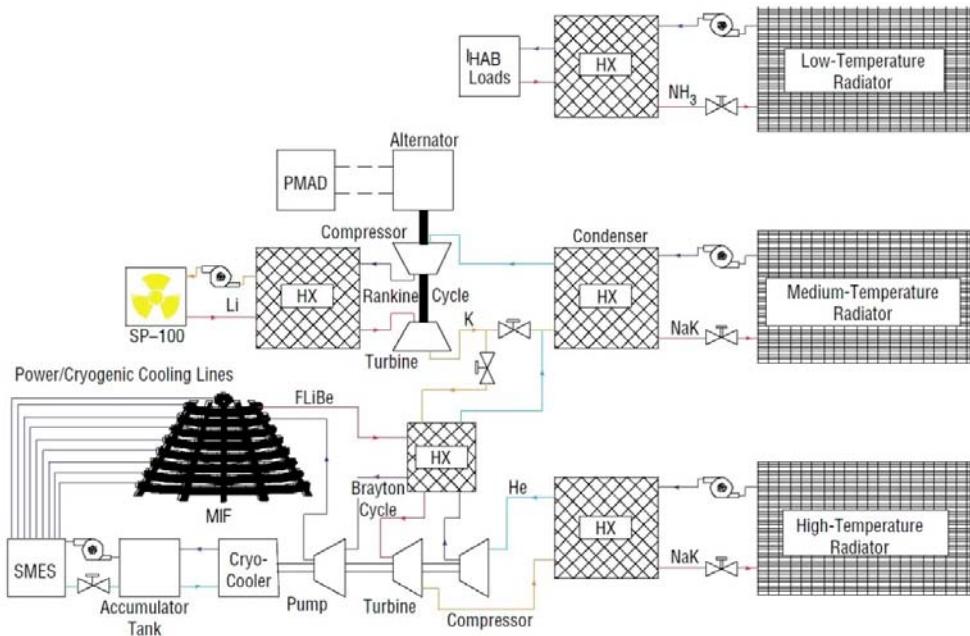

Figure 10 – Vehicle power, thermal rejection schematic

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STRUCTURAL CONSIDERATIONS

Due to the size of this vehicle, it will be necessary for it to be assembled in space. The components must be designed for modular assembly and be small enough for launch on a conceivable heavy launch vehicle. A few components, such as the tanks, would be analyzed for launch loads, but nearly all components will be launched in a stowed configuration. This will produce lower vehicle structural loads, because the vehicle would not be required to withstand launch from Earth as an integrated structure. Most of the vehicle structure will consist of an aluminum truss.

The 2010 Z-Pinch study configuration is a 125 meter long vehicle with the crew compartment and landing vehicles at the front end of a long square truss and the main nuclear propulsion system at the aft end. The engine nozzle and most of the structure to the right of the hashed line shown in Figure 1 is the HOPE vehicle configuration. The radial capacitor banks are a Z-Pinch design plus a more recent analysis suggests an 8-spline magnetic nozzle with variable spline cross-sections and ring assemblies embedded into 8 structural rings would provide an optimized nozzle design.

The engine nozzle could be made of a Carbon Composite (C/C) material, such as a graphite epoxy composite IM7/8552, to provide stiffness and low mass. The magnetic field generated in the nozzle will protect the nozzle structure from the high-temperature fusion plasma, but, gamma radiation and neutrons will emanate spherically outward from each fusion pulse. Because the capacitor banks must be kept in close proximity to the top of the magnetic nozzle to provide high voltage pulses to the nuclear fuel, they will be particularly susceptible to radiation damage. A radiation shield cap whose composition is detailed in Figure 11 will extend down from the top of the nozzle, protecting a radial half-angle wide enough to shield the entire vehicle, particularly the capacitor banks.
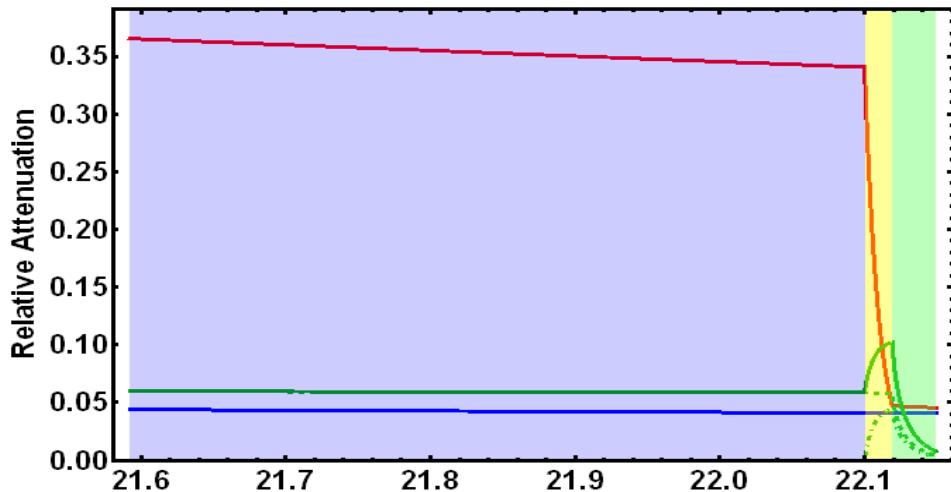

Figure 11 -Radiation Shielding Thickness: 22 cm Lithium Hydride (LiH) will capture ~ 95% of the high energy neutrons. Boron Carbide (B_4C) effectively captures thermal neutrons, but releases gamma rays, and a thin Tungsten layer reduces the gamma rays
Attenuation: Red = Thermal neutrons, Green = Gamma rays, Blue = 14.1 MeV neutrons.

The dimensions and stress requirements of the magnetic nozzle structure are based on the fusion engine performance and loads calculated for an approximately 14 meter exit diameter nozzle. A simplified Finite Element Model Analysis and Post-processing (FEMAP) model was created to analyze the nozzle structure and optimize its design and mass. Material susceptibility and shielding capability against fast neutrons produced by the fusion process are important in nozzle and vehicle configuration, so a large Margin of Safety (MOS) must be assumed for the nozzle structure due to the frequent radiation flux it must endure. The axial and lateral forces of the fusion pulse are applied to a segment of the 8 ring assemblies, each a different length and distance from the fusion explosion. The loads are then

transmitted through structural splines and struts against the base of the vehicle truss. A fixed boundary that represented a very large mass is placed at the top of the struts, as a conservative approximation. After the model was meshed, a positive static FEA result was obtained with a FEMAP/NASTRAN solver using existing Titanium and C-C material physical properties. Dynamic frequency and life analysis was not performed. A simplified thick-walled tubular model of 1/8 of the nozzle, representing thermal fluid channels, was optimized with varying wall thickness rather than cross-sectional dimension, was then optimized for minimum mass. This sectional model was revolved 360 to obtain the nozzle represented in Figure 12.
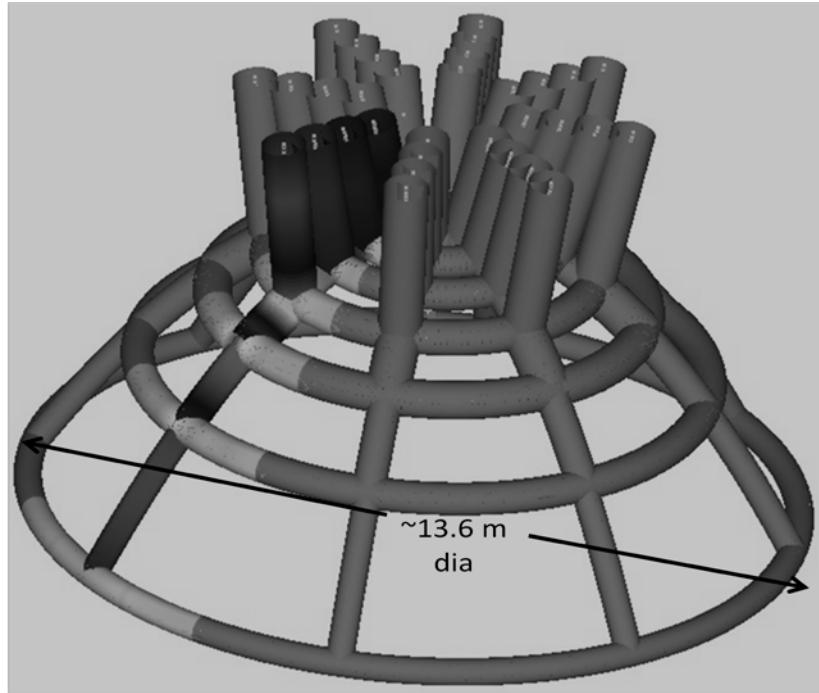

Figure 12 – Revolved FEA model of magnetic nozzle

MISSION ANALYSIS FOR A BEST ESTIMATE VEHICLE MASS

The thrust levels of a Z-Pinch fusion rocket are similar to traditional chemical propulsion systems; however, the mass of the propulsion system results in accelerations in the milli-g range. The outstanding specific impulse of the propulsion system enables high overall system performance. Traditional chemical propulsion systems operate in the 1-g acceleration range, allowing for the assumption of impulsive burns for trajectory analyses because the burn time is relatively short compared to the overall trip time. The Z-Pinch propulsion system's milli-g accelerations place it in the category of "medium thrust" trajectory analysis, so the burns were numerically integrated and patched into a transfer conic trajectory.

Several simplifying assumptions were made for this analysis. No ephemeris data and simple circular orbits at the mean orbital radius were used to represent the departure and arrival planets. While the results are valid for required transfer energies, the epoch of the mission and stay time at the destination were not quantified in this analysis. The arrival conditions for each leg were set at a v infinity of 0 km/s. The planetary orbit component of the trajectories was not assessed and no parking orbit analysis was performed. Escape burns should account for approximately 10% of the propellant load, but they have not been assessed in this analysis.

For a given payload mass of 150 mT, Z-Pinch offers a 50% reduction in the nominal one-way trip time compared to a chemical propulsion mission. The 90-day trajectory has a 1.5 day Earth departure burn.

The total burn time is 5 days for a roundtrip Mars mission, equating to 27,500 m/s of ΔV and using 86.3 mT of propellant. The trajectory for a 30-day trip to Mars requires an 8.7 day Earth departure burn. For a roundtrip, this trajectory requires a total burned propellant load of 350.4 mT and has an equivalent ΔV of 93,200 m/s. While these numbers are significantly larger than the 90-day trajectories, this does show the feasibility of a 30-day trip to Mars. Trip time, propellant, and Delta V are compared in Table 2 for a vehicle with a 552 mT burn-out mass, which is in the range of the study's "Best Estimate" mass shown in Table 3.

A comparison of the payload mass fractions shows that only about 33% of the mass in the traditional, high-thrust chemical propulsion Mars cargo mission could be payload. The Z-Pinch propulsion system can deliver a higher payload mass fraction, estimated at 35-55% in half the time, (90 days vs. 180 days). Z-Pinch propulsion may also enable fast round-trip trajectories for human Mars missions with comparable payload mass fractions to current chemical propulsion vehicle estimates.

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

Table 2 – Trip time, propellant and Delta V

Subsystem	Mass (kg)
Payload – crew habitat, lander, small transport, radiation protection, ECLSS equipment and consumables for crew quarters	150,000
Structures – Main truss, main propulsion tanks, secondary structure for systems below	31,500
Main Propulsion – MIF nozzle, magnetic coils, neutron/gamma shielding cap, capacitor/Marx generator recharge system	115,000
Thermal Management – radiators, pumps, tanks, cryo-coolers, thermal fluids	77,000
Power Systems – fission reactor, radiation shield, distribution lines	16,500
Avionics & RCS – control boxes, sensors, communication & Reaction Control System (RCS)	2,300
Total Dry Mass	**392,300**
30% Mass Growth Allowance	117,700
Main propulsion & RCS propellant – for 90-day Mars roundtrip	87,900
Total Mass (Best Estimate)	**597,900**

Table 3 – Vehicle mass estimate breakdown for 90-day Mars roundtrip

FUTURE WORK

The technology development required for this propulsion system is achievable on a reasonable timescale given sufficient resources. The first stage of a development program would involve sub-scale experiments to establish the foundational aspects of the system, such as Z-Pinch formation utilizing annular nozzles. Furthermore, the experiments would yield quantitative information enabling more sophisticated configurations for test and evaluation. The ACO study provided a tangible vehicle concept for the application of Z-Pinch fusion propulsion and aided in the successful proposal bid to fund utilization of the DM2 module in a propulsion development program at Redstone Arsenal (RSA).

Several key technologies that warrant development to produce the first fusion propulsion system are listed in Table 4. These are covered in the development plan envisioned for the Z-Pinch Test Facility at RSA, in Huntsville, Alabama.

		TRL Level
❋	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

Table 4 – Key Technology Readiness Levels (TRL) estimates

Z-PINCH TEST FACILITY

DM2 stands for Decade Module 2, a ~500 kJ pulsed power facility. The DM2 was the last prototype serving as a test bed for the design and construction of the much larger Decade Machine, which was built and utilized at Arnold Air Force Base in Tennessee for nuclear weapons effects (NWE) testing. DM2 was built by Physics International around 1995; it has had an active and important role in the development of advanced Plasma Radiation Sources (PRS) for the Defense Threat Reduction Agency's (DTRA) cold X-ray source development program.

DM2 is one of the latest inductive energy storage, pulse power machines and is an excellent research platform for a university pulsed power or plasma physics research branch. Despite over 10 years of use, the unit is in good working order and has had a reliable operating history.

UAHuntsville has teamed with L3 Communications, who have arranged for the transfer of government equipment to a UAHuntsville-managed secure facility: the Aerophysics Facility located on RSA. See Figure 13. A sustainable business model for the long-term use of DM2 is being developed with L3 and Dr. Bill Seidler, Senior Technical Fellow at The Boeing Company, who was actively involved in the DECADE program and is providing invaluable mentoring in DM2 utilization.

Experiments carried out on wire array Z-Pinch machines use multiple diagnostic methods to observe the behavior of the implosion process from initiation to stagnation. Any experiments carried out for this Z-Pinch propulsion concept will also accommodate the same diagnostic methods. A list of possible diagnostics useful for such an experiment would include the following:

- X-ray diodes (XRD)
- Tantalum Calorimeters
- Zipper Array
- CCD-based extreme ultraviolet (XUV) transmission grating spectrography
- Laser shearing interferometer (LSI)
- Planar laser induced fluorescence (PLIF)
- Magnetic probes: B-dots, flux loops, Rogowski coils, Pearson probes, etc.
- Langmuir probes
- Mach-Zehnder interferometer (multiple chords)

Figure 13 – Aerophysics facility located on RSA

DEVELOPMENT PLAN

Many key questions have already been discussed by the team and the main concern is the operation of the thruster concept. The key objectives have been broken down as follows:

1. How will the Z-Pinch work in this propulsion vehicle configuration and what is its functionality in relation to the rest of the system?
    a. This will involve sizing the Z-Pinch. The state-of-the-art Z-Pinch size is only a few centimeters, although experiments capable of achieving Z-Pinch plasmas up to one meter in length exist.
    b. Via our experimental observations of compression, neutron flux, power output, etc. the scaling of models and physical structures will guide successive experiments.
2. Can the Li^6 liner be made to work in the desired fashion?
    a. How will the lithium be handled, stored, using what materials?
    b. How will it be injected into the system and at what state (solid, liquid, gas, plasma)?
    c. Before attempting to use lithium, should a safer metal, such as gallium, be considered or tested?

3. If the Li^6 liquid liner concept is shown to function adequately, how can a magnetic nozzle be designed and constructed to direct the exhaust elements?
    a. What materials should be used?
    b. How might an MHD generator be incorporated for partial recharge of the power systems?
    c. How will the flow be redirected?
    d. How can important parameters such as specific impulse and thrust be measured or inferred?
4. How can the system gain be measured or inferred using DM2?
    a. What are the different scaling relationships that can be utilized to direct future experiments?
    b. What experiments can be performed to determine optimum fuel mixing ratios, and how might they be incorporated into the overall process?
    c. What methods can be used to mitigate, handle radiation from the machine?
5. Magnetic nozzle design trades.
    a. Variation in the number and location of the nozzle rings.
    b. Variation in the minor radius of each nozzle ring.
    c. Variation in the position of the parabolic focus.
    d. Variation in current amplification factor.

An estimated schedule of how the experimental program might be built up from a single DM2 to a break-even facility is outlined in Table 5. A break-even facility is one that put out as much or more energy as is input. Given the right technology and resources, development of each experimental stage, i.e. the design and construction of evolutionary Decade Modules, would occur in parallel with experiments/tests.

Experiment Stage	# Years
DM2	3
Single Decade Quad	2
4 Decade Quads	2
8 Decade Quads (1 full ring, see Figure 14)	2
2 Full Rings (Break-even)	2
	Total: 11 years

Table 5 – Estimated Schedule of Experimental Program

Single DM2 Capacitor Module

Four DM2 Modules

32 DM2 Modules

Charge transmission lines not shown
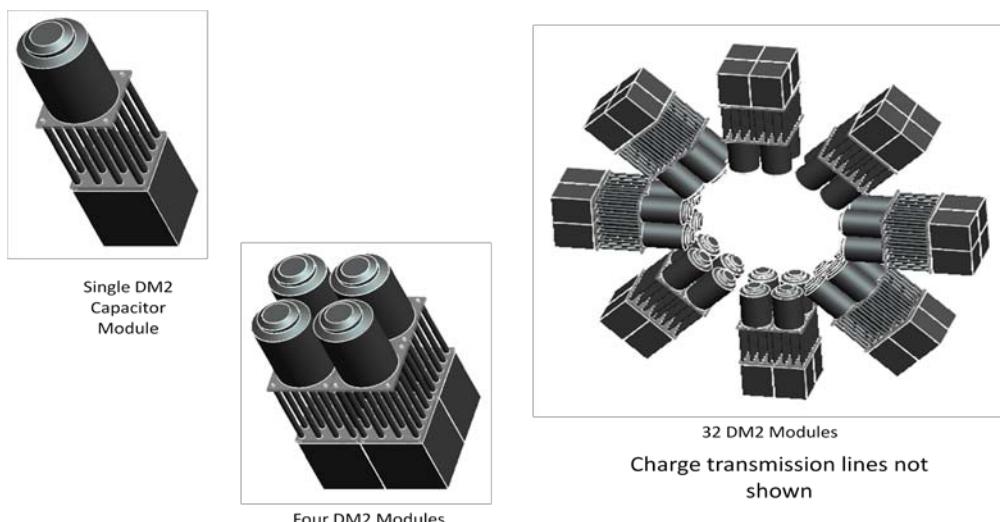
Figure 14 – DM2 Assembly Concept

SUMMARY AND CONCLUSIONS

Fusion-based nuclear propulsion has the potential to enable fast interplanetary transportation. The large size of an interplanetary vehicle dictates that it will be assembled in space. Due to the great distances between the planets of our solar system and the harmful radiation environment of interplanetary space, high specific impulse (I_{sp}) propulsion vehicles with high payload mass fractions have a practical advantage of providing fast transit through a hazardous environment for human spaceflight missions.

Analysis of the Z-Pinch propulsion system concludes that a 40-fold increase of I_{sp} over chemical propulsion is predicted. An I_{sp} of 19,436 sec and useful thrust of 38 kN for 150 mT payload, a nearly doubling of the predicted payload mass fraction, warrants further development of enabling technologies.

The vehicle can be designed for multiple interplanetary missions and conceivably may be suited for an automated one-way interstellar voyage.

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FUSION PROPULSION Z-PINCH ENGINE CONCEPT

5TH SPACECRAFT JOINT SUBCOMMITTEE MEETING OF THE JOINT ARMY NAVY NASA AIR FORCE (JANNAF)

DECEMBER 5, 2011
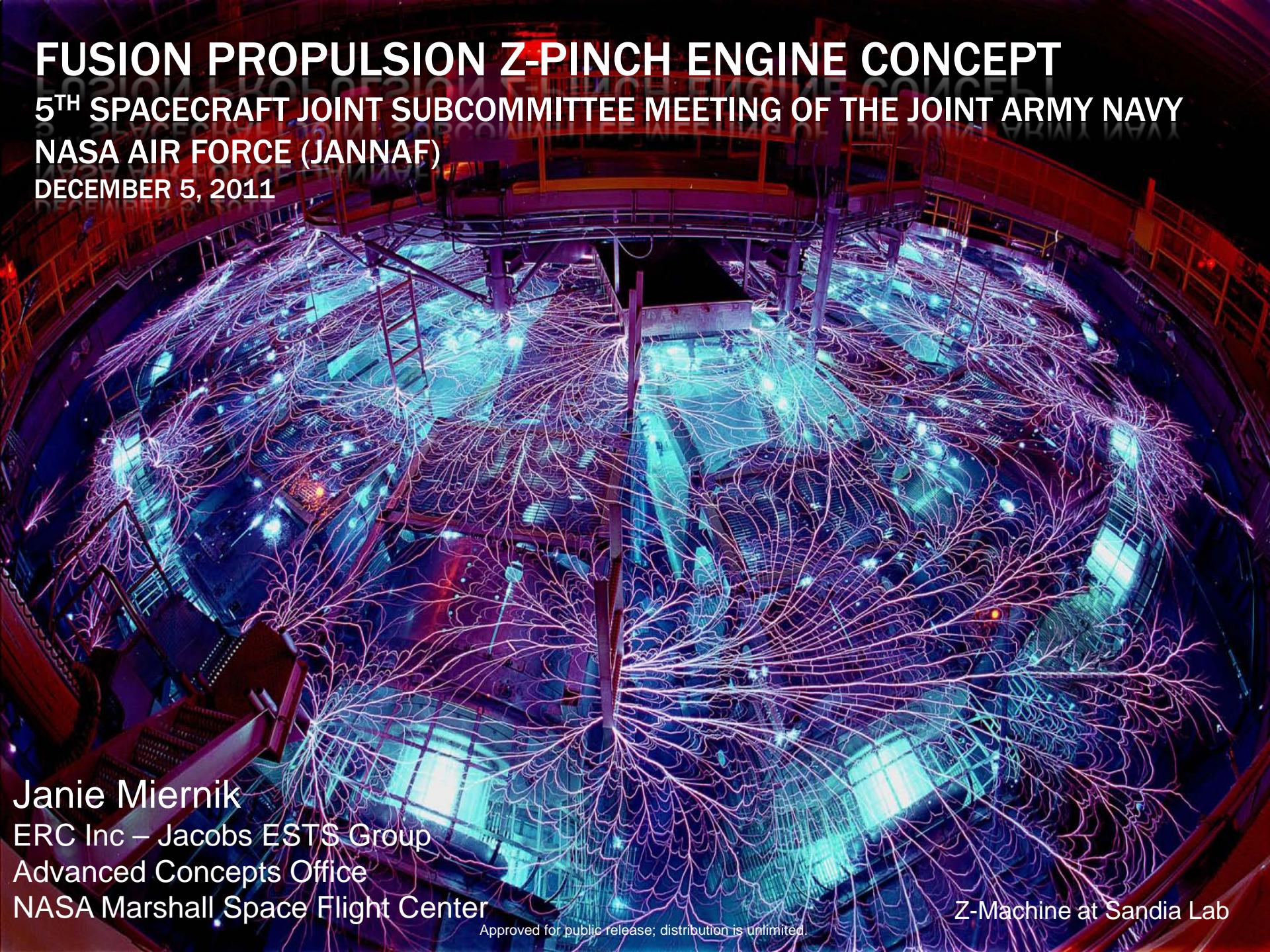
Janie Miernik
ERC Inc – Jacobs ESTS Group
Advanced Concepts Office
NASA Marshall Space Flight Center

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.

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

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

Hypersonic
nozzle
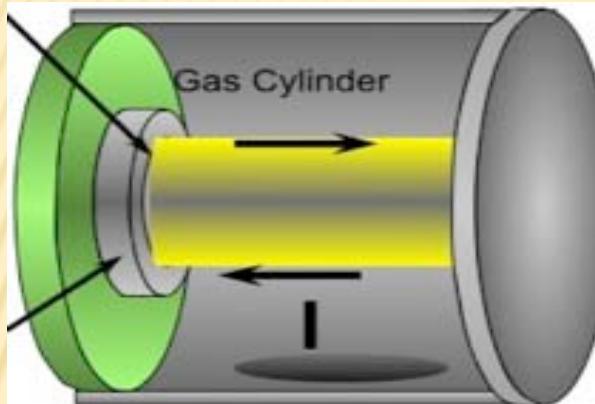
1) **Gas Injection &
Preionization**

Anode

Cathode

Evacuated
Chamber
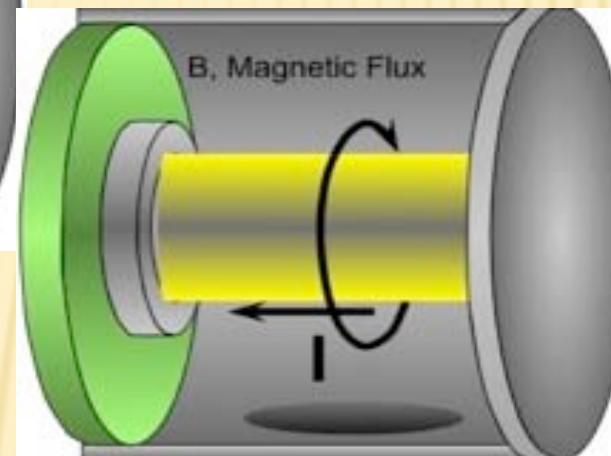
2) **Initial
Implosion**

3) **Implosion/stagnation**
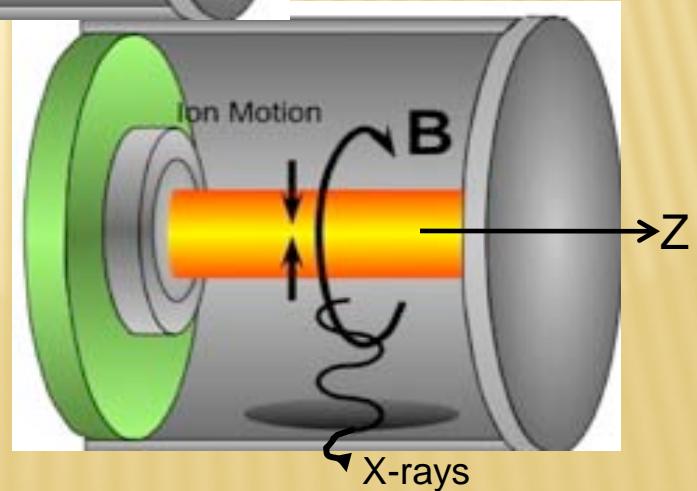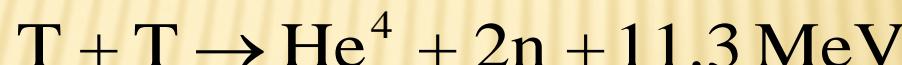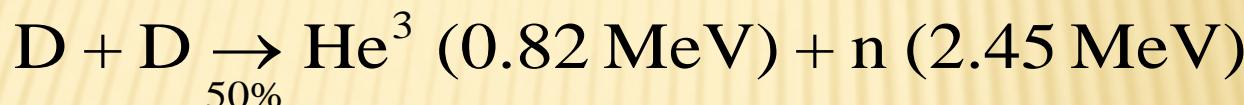
X-rays

PRIMARY REACTIONS

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

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

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

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

$$T + T \rightarrow He^4 + 2n + 11.3 \, MeV$$
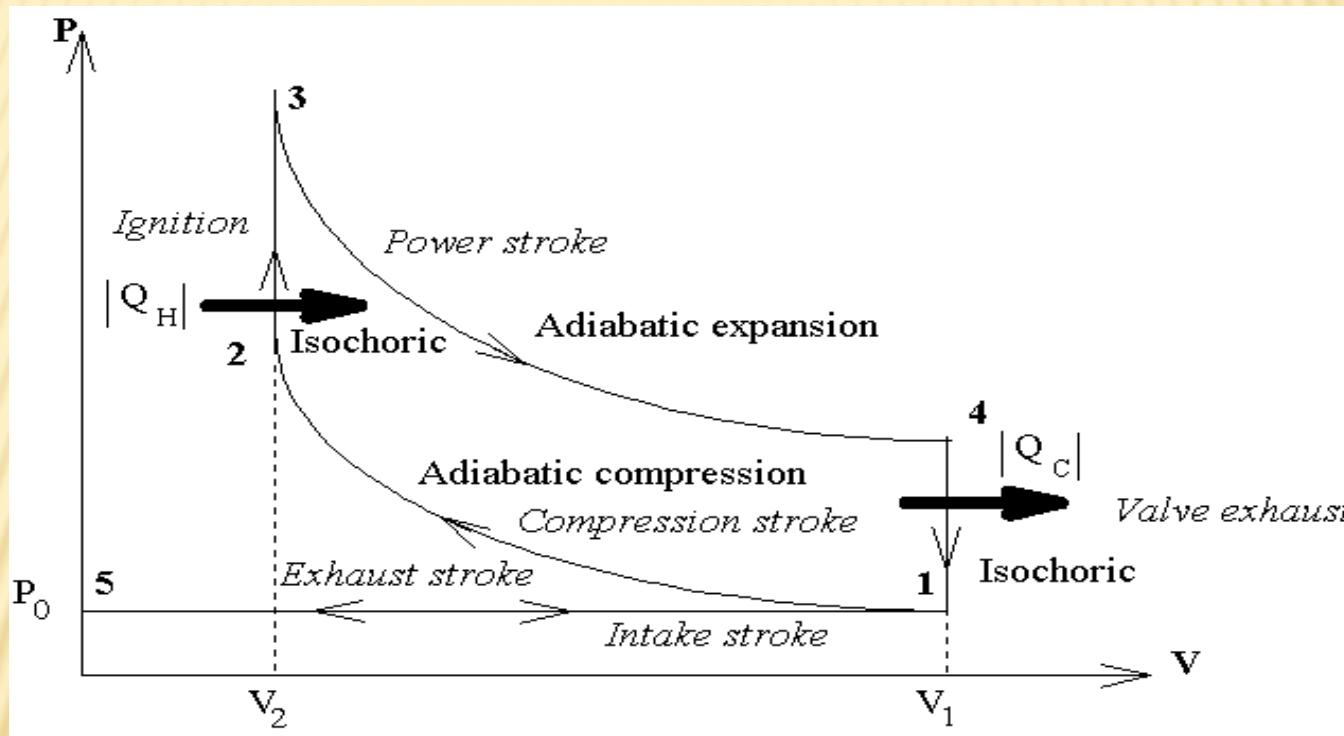
Pulse Frequency	10 Hz
Driver Energy Density	10 kJ/kg
Compression Ratio (R_1/R_2)	10
Initial DT Fuel Mass	100 mg
Lithium Liner	200 x m_{DT} (20 g)
Ignition Temperature	20 keV

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.

Secondary Reactions: Li^{6}D Release 22.4 MeV

Li^6-n, 4.8 MeV

t = 50 ns

D, T, He^4 Plasma

e$^-$

e$^-$

Primary Reactions: DT Release 17.6 MeV

DD Release 4.0 MeV
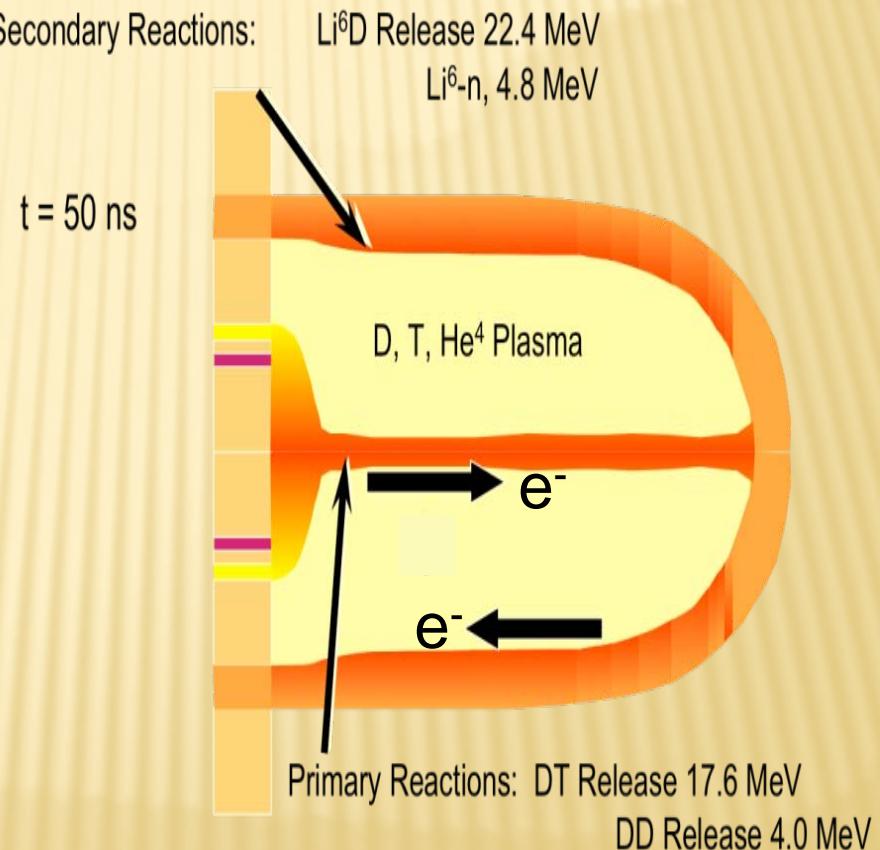
MAGNETIC NOZZLE PERFORMANCE MODEL

- 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
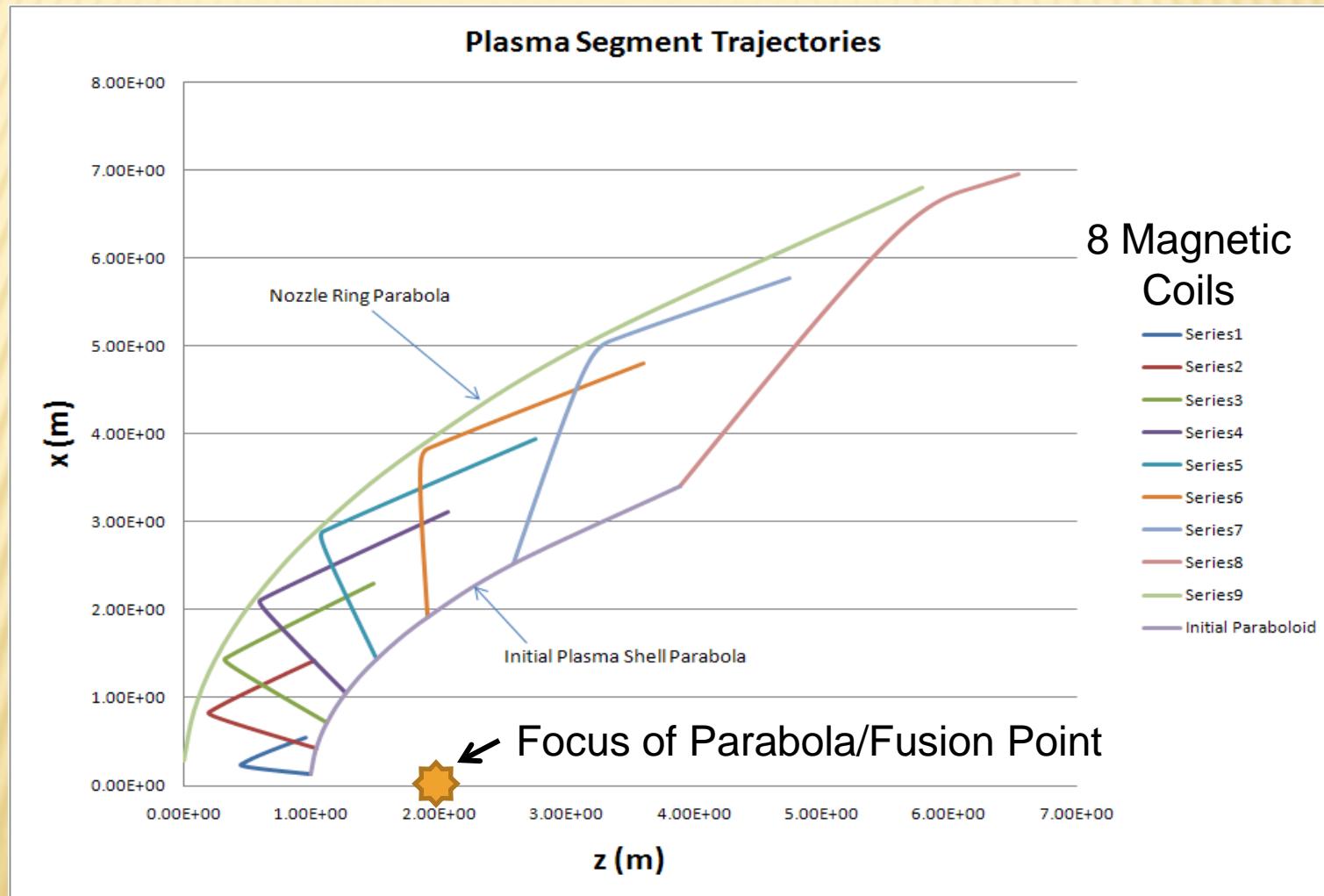
Z-Pinch Pulsed Propulsion (cont.)

✳ 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.

a)

b)

c)
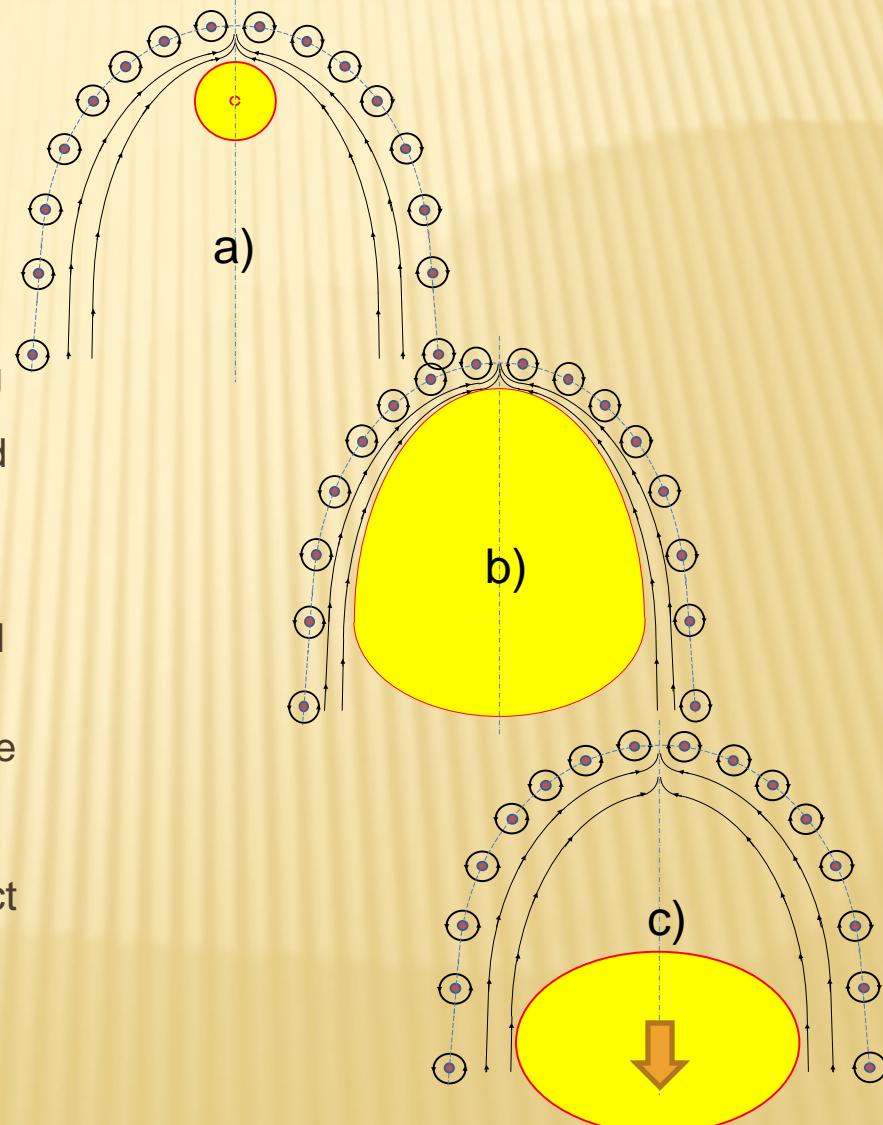
Z-Pinch Pulsed Propulsion (cont.)

- � 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).

Z-Pinch
Anode
Rings x-sec
Secondary Fuel And Radiation Shield
D-T Fuel
Cathode

Capacitor bank
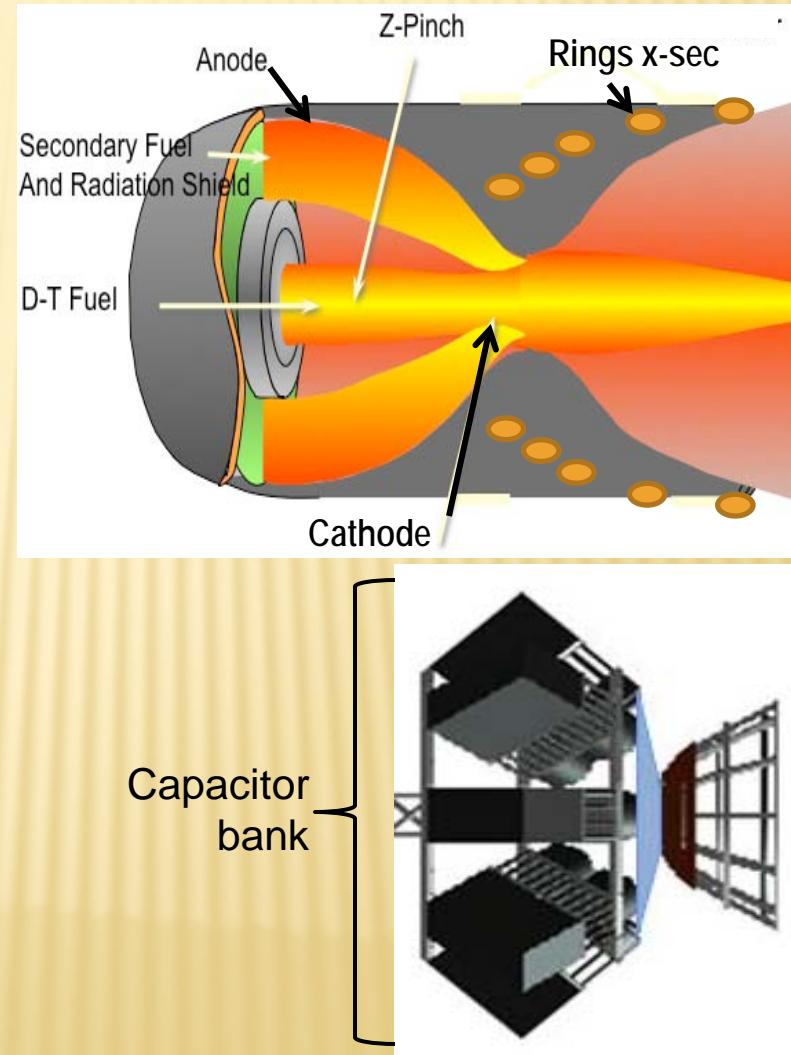
Z-PINCH FUSION MAGNETIC NOZZLE

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.
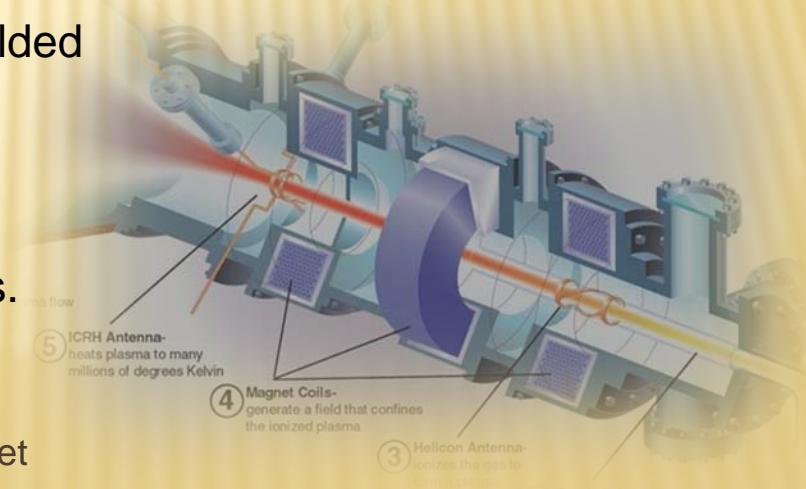
* Variable Specific Impulse Magnetoplasma Rocket

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
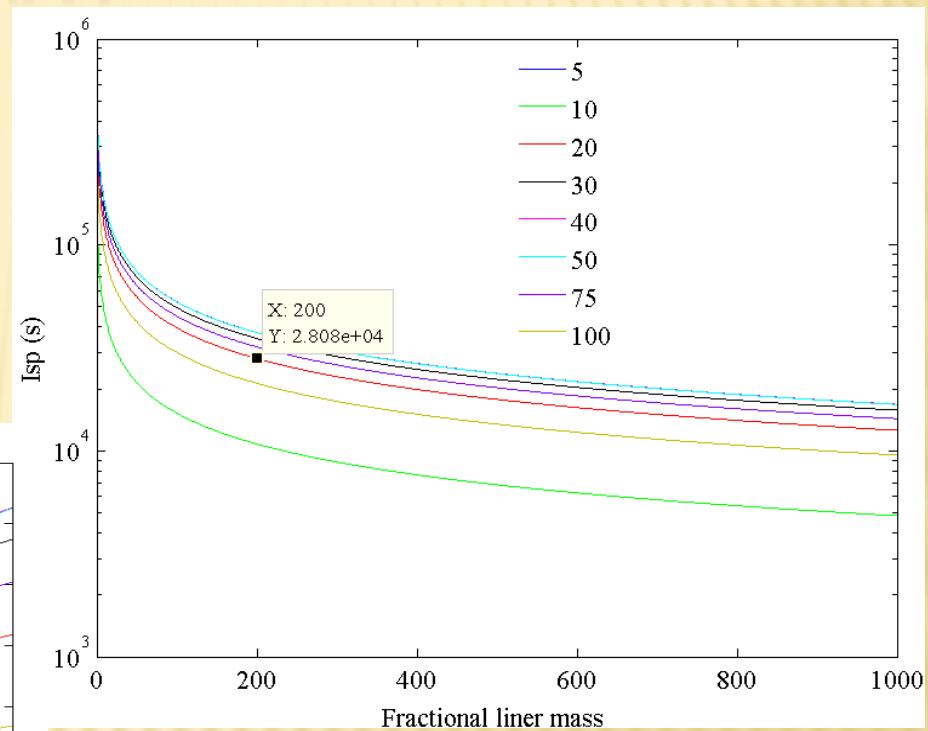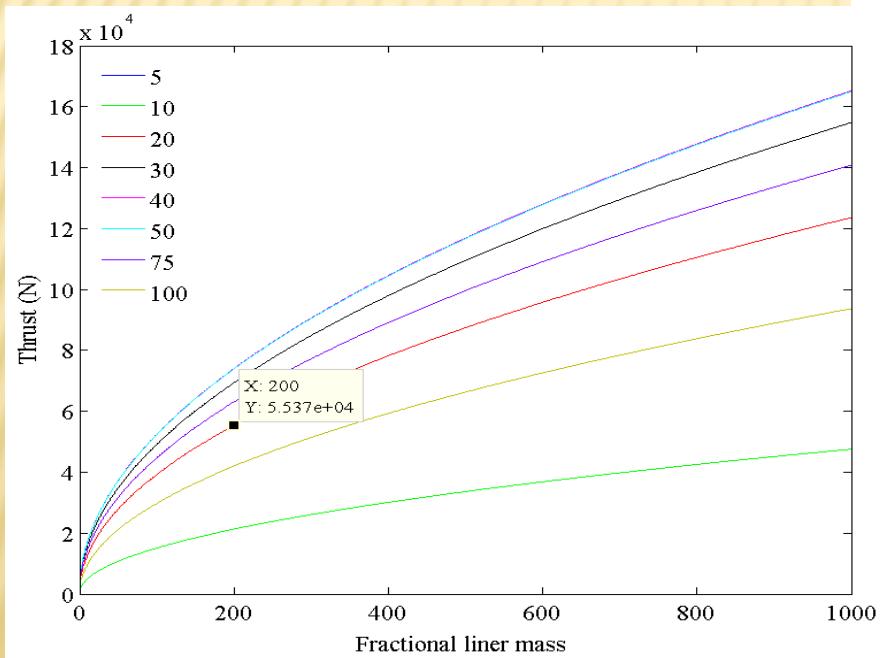
MAGNETIC NOZZLE COILS

- 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.

NOZZLE COILS
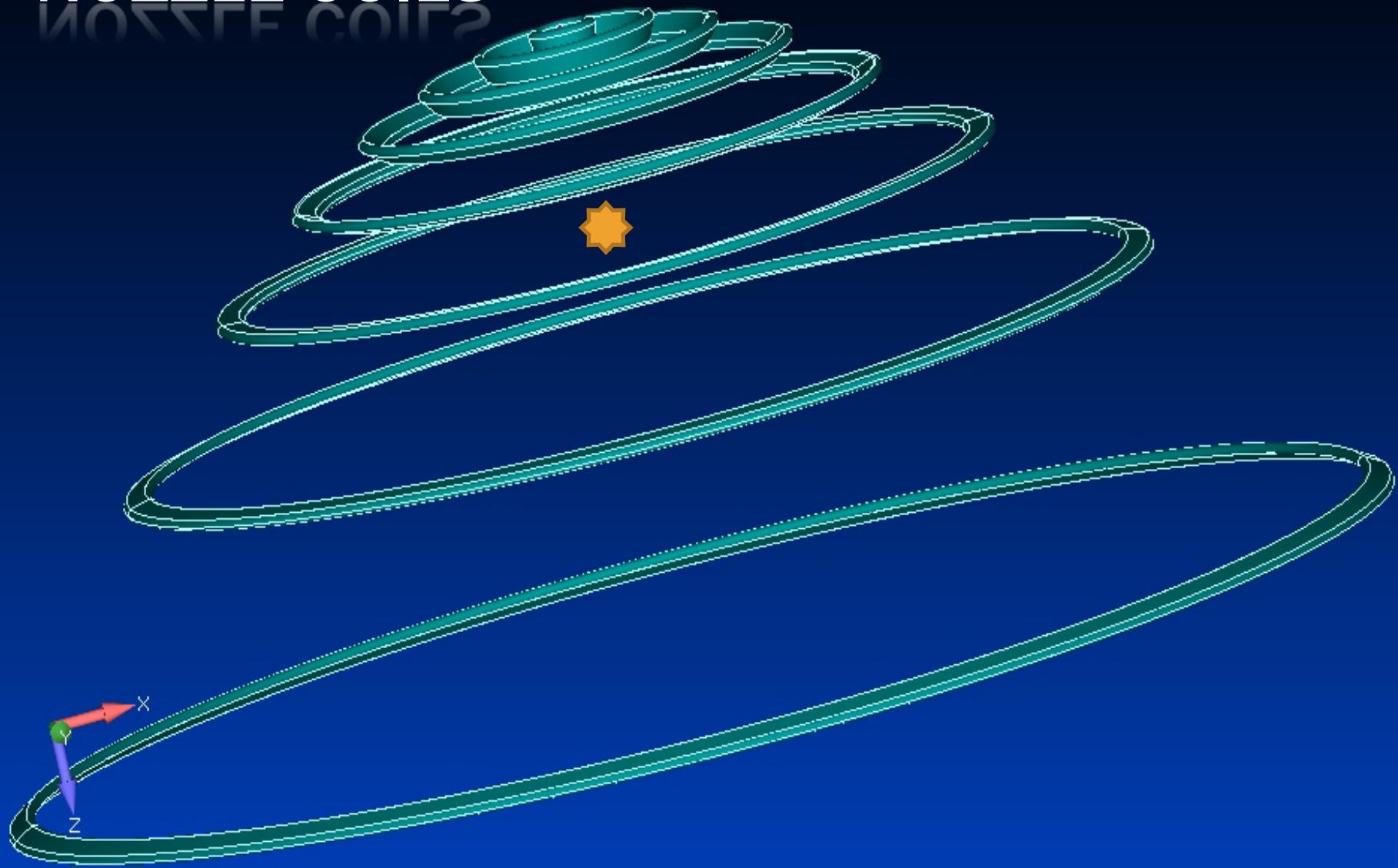
# Z-PINCH THRUST COIL X-SECTION

30 cm

Thrust Coil Load Structure

Thrust Coil Conductor Mo TiB$_2$ metal matrix composite

Neutron protection/cooling channel

Zirconium diboride (ZrB$_2$) ceramic shell

C-C Coil Load Structure

LN2 coolant channel

Molten mixture of lithium fluoride (LiF) and beryllium fluoride (BeF$_2$) [FLiBe]

Direction of Fusion pulse

Seed Field Coil Housing

Radiant Heat Shield

Seed Coil Load Structure

Kapton Insulator

Seed Field Superconductor YBa$_2$Cu$_3$O$_7$ and LN$_2$ coolant channel

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.

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

1/8th of nozzle

Ti Stress Limits

~13.6 m dia
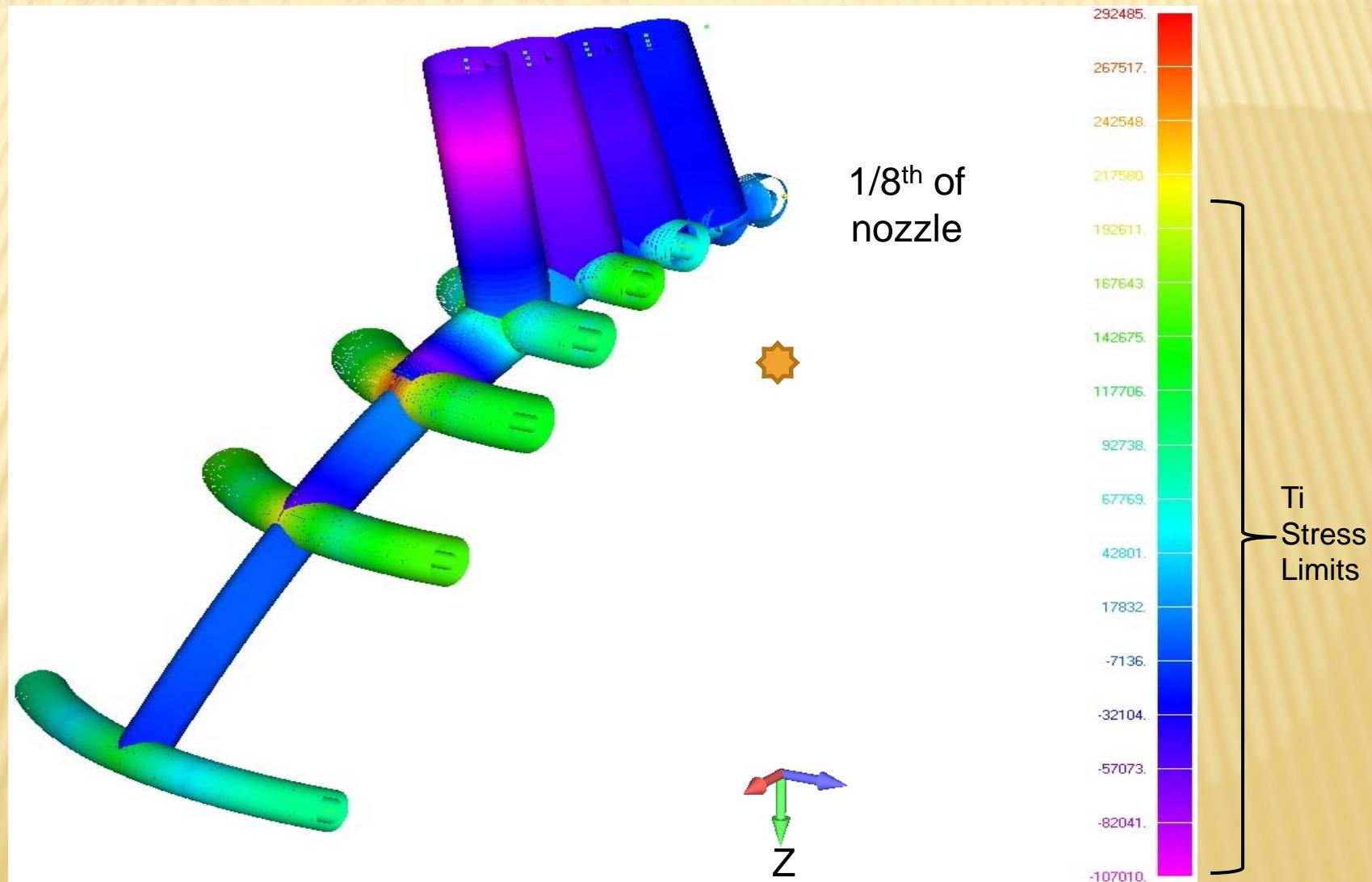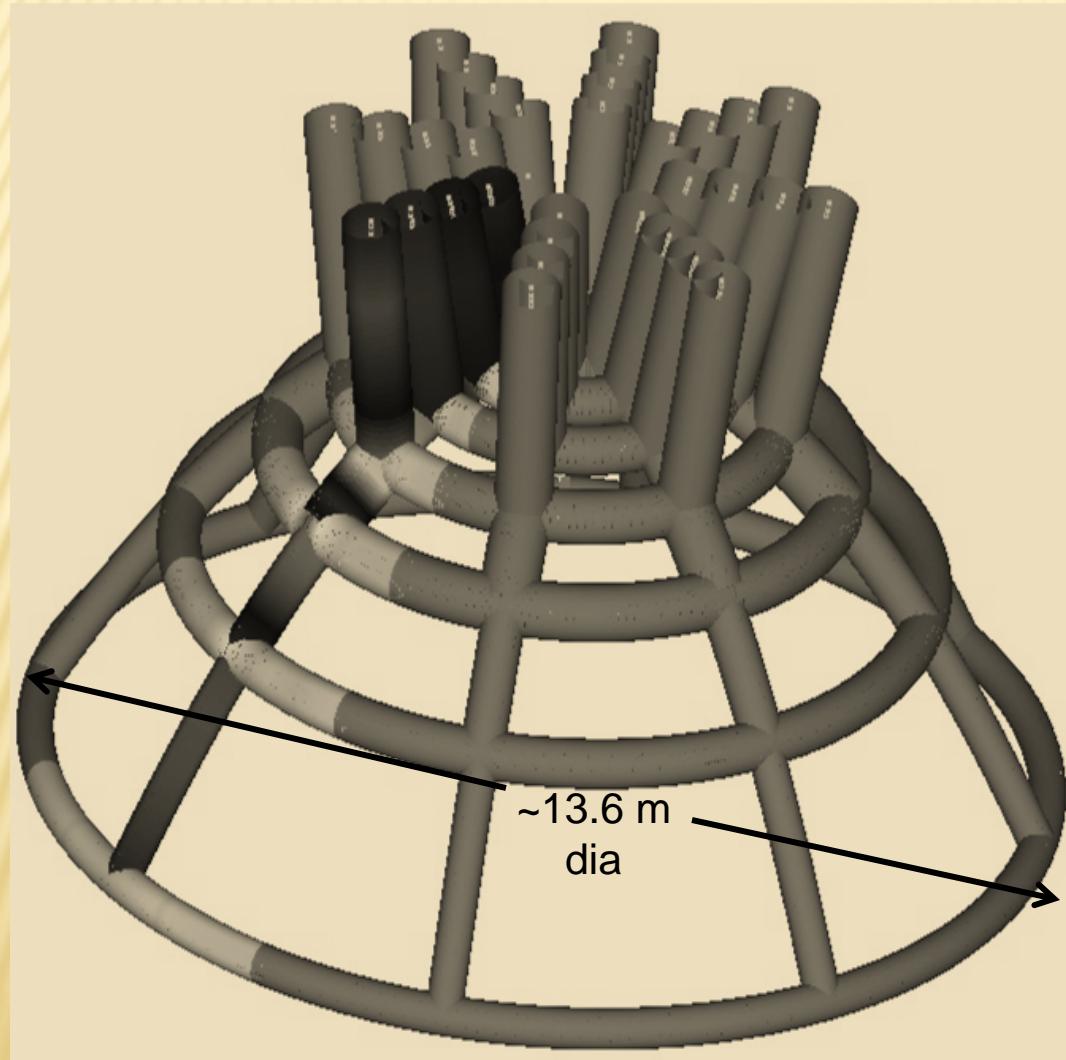
• Thick-walled tubing was modeled to simulate fluid passages for coolant/FLiBe.

• 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$_4$C) 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.
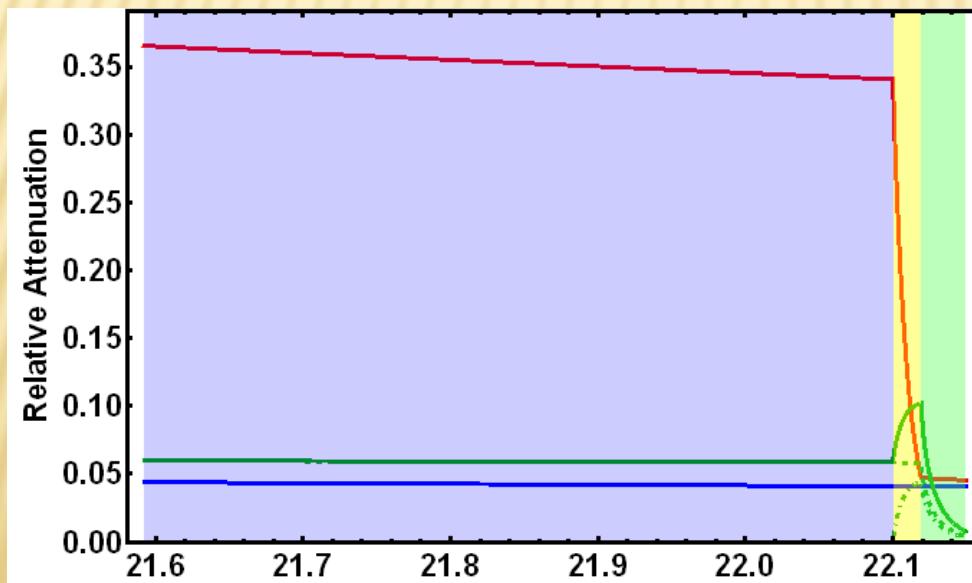
Radiation Shielding Thickness (cm) and Attenuation:
•Blue = 14.1 MeV neutrons.
•Red = Thermal neutrons.
•Green = Gamma rays.
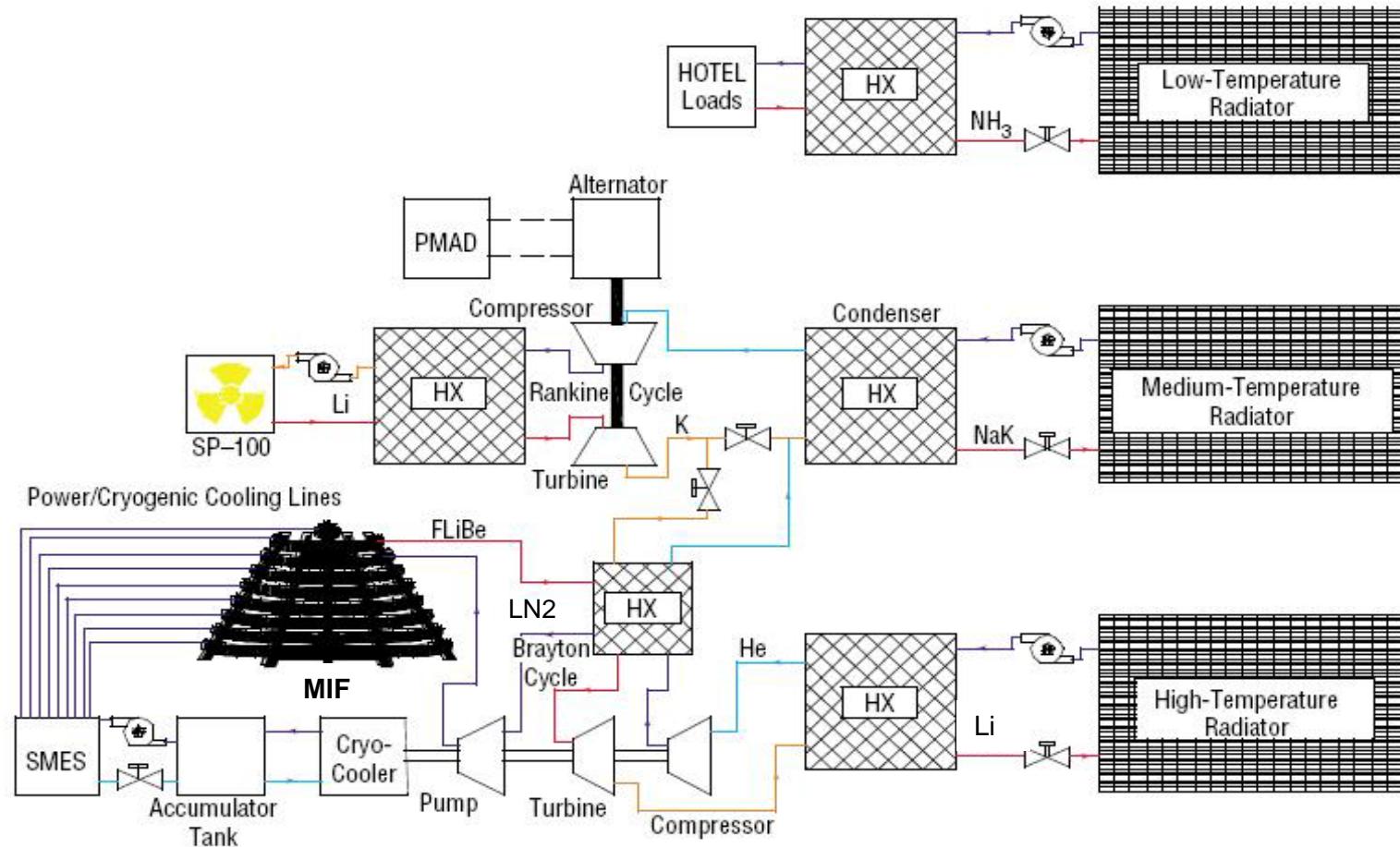
MISSION ANALYSIS

- ❋ 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.

→

Legend:
- Mars Orbit (red)
- Earth Orbit (blue)
- Transfer Traj Orbit (green)
- Transfer Trajectory (magenta)
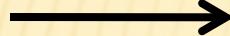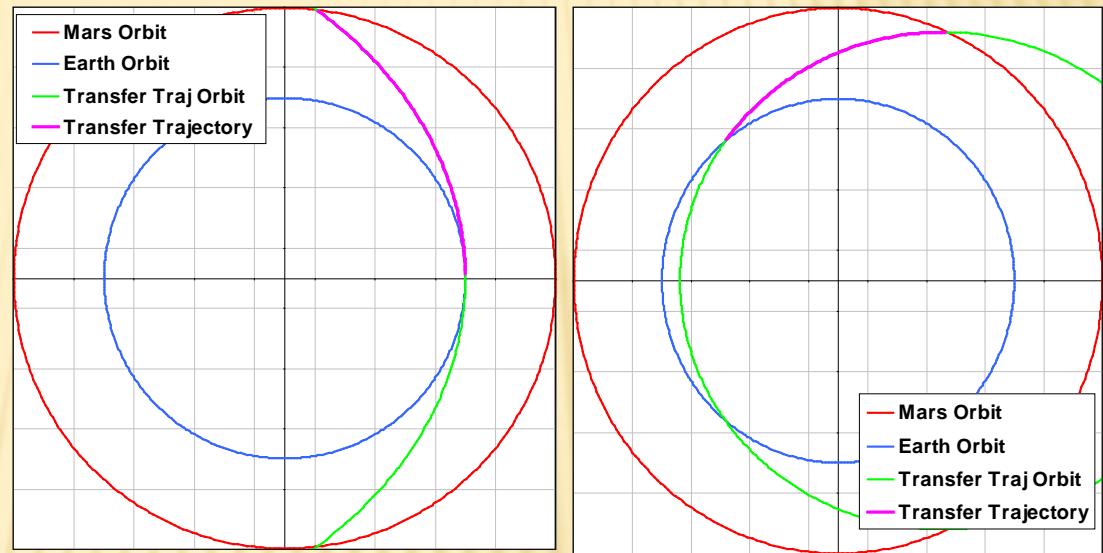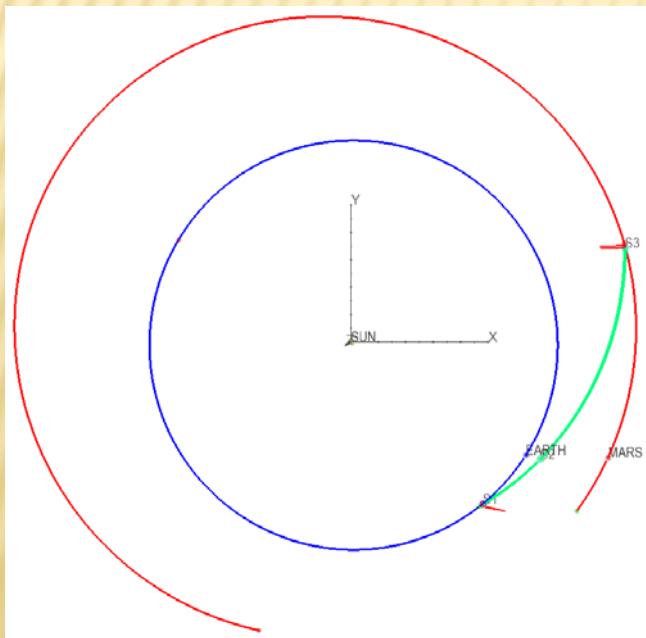
← An optimal 90-day outbound trajectory to Mars departing Earth August 1, 2035.
In all trajectories, the burn time is so small compared to the coast time that these burns are not visible on the full trajectory plots.

MISSION DELTA V

VEHICLE CONCEPT

Fusion Propulsion

RCS

Capacitor Banks

Habitat

Magnetic Nozzle

Fission Power Plant

Lander

MIF Propulsion

Radiators

HOPE MTF Vehicle

125 m
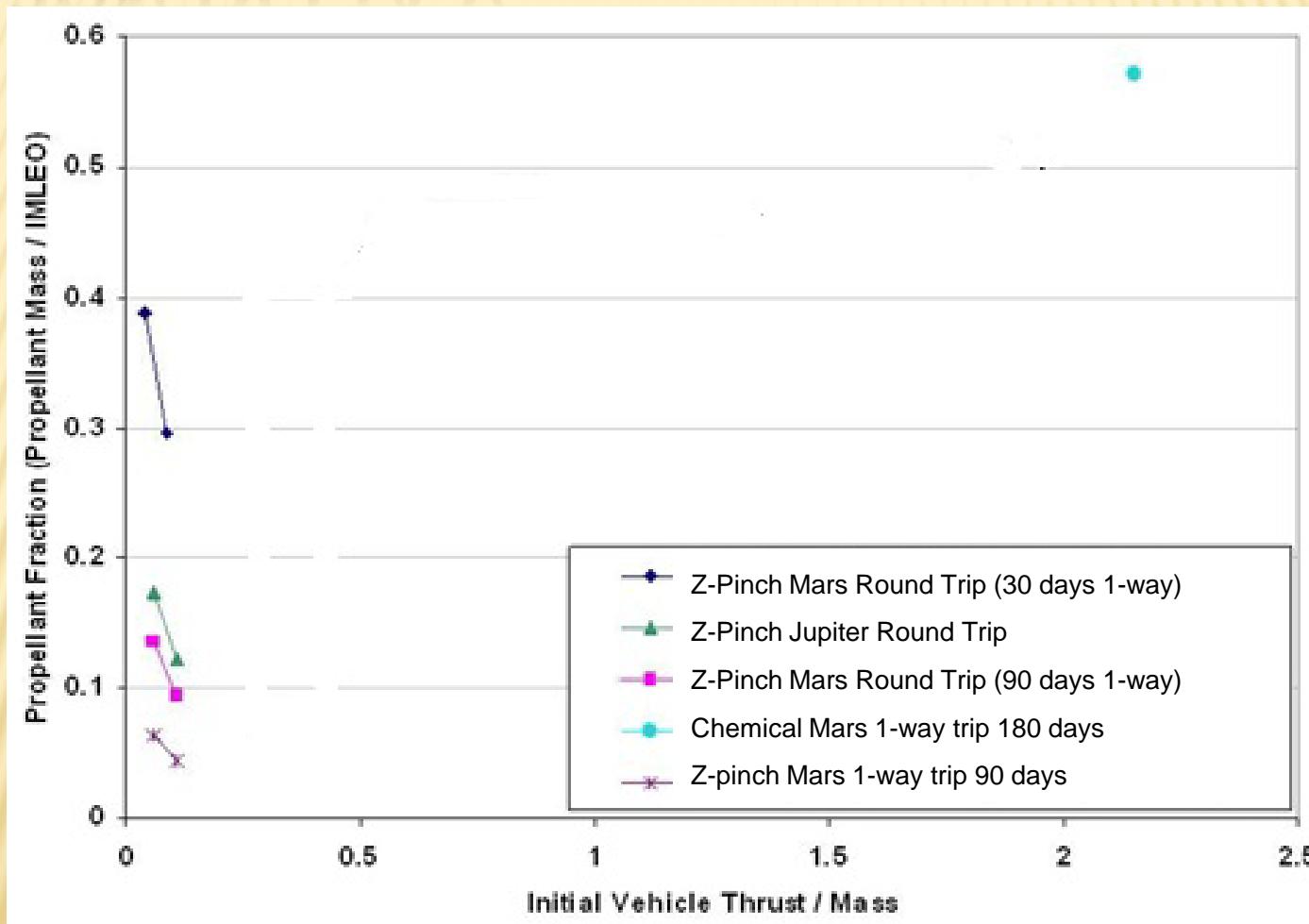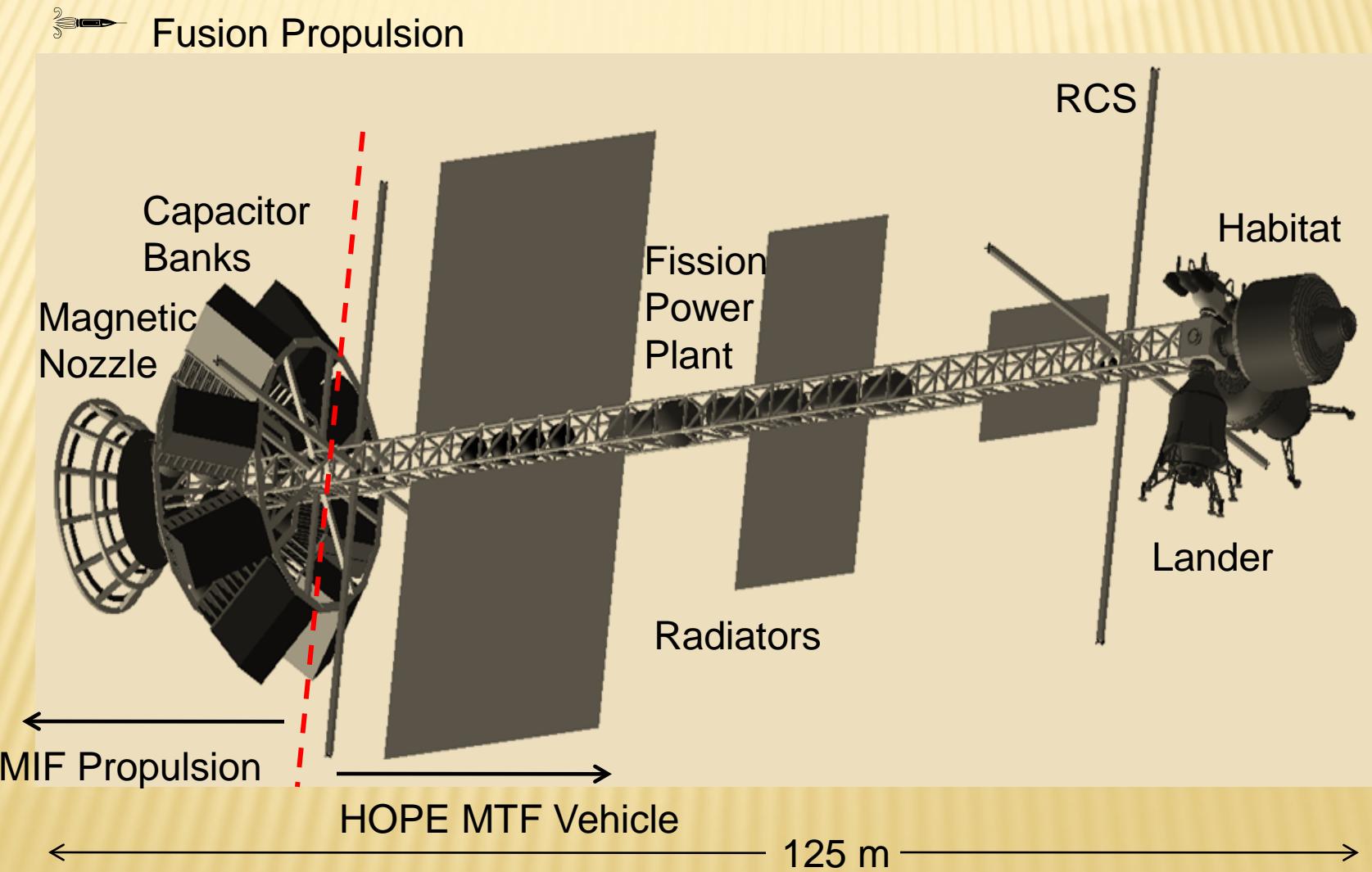
MASS ESTIMATE

| Subsystem	Mass (kg)
Payload – crew hab, lander, consumables, small transport, radiation protection and ECLS equipment for crew quarters.	150,000
Structures – Main truss, main propulsion tanks, secondary structure for systems below	31,500
Main Propulsion – MIF nozzle, magnetic coils, neutron/gamma shielding, capacitor/Marx generator recharge system	115,000
Thermal Management – radiators, pumps, tanks, cryo coolers, thermal fluids	77,000
Power Systems – fission reactor, radiation shield, and dedicated cooling loops	16,500
Avionics – control boxes, sensors & Reaction Control System- tanks and RCS	2,300
Total Dry Mass	392,300
30% Mass Growth Allowance	117,700
Main propulsion & RCS propellant – for 90-day Mars Round trip	87,900
Total Mass (Best Estimate)	**597,900**

NWE TEST ARTICLE – DM2*

DM2 modules were prototypes for the Decade Machine at Arnold AF Base for NEW testing

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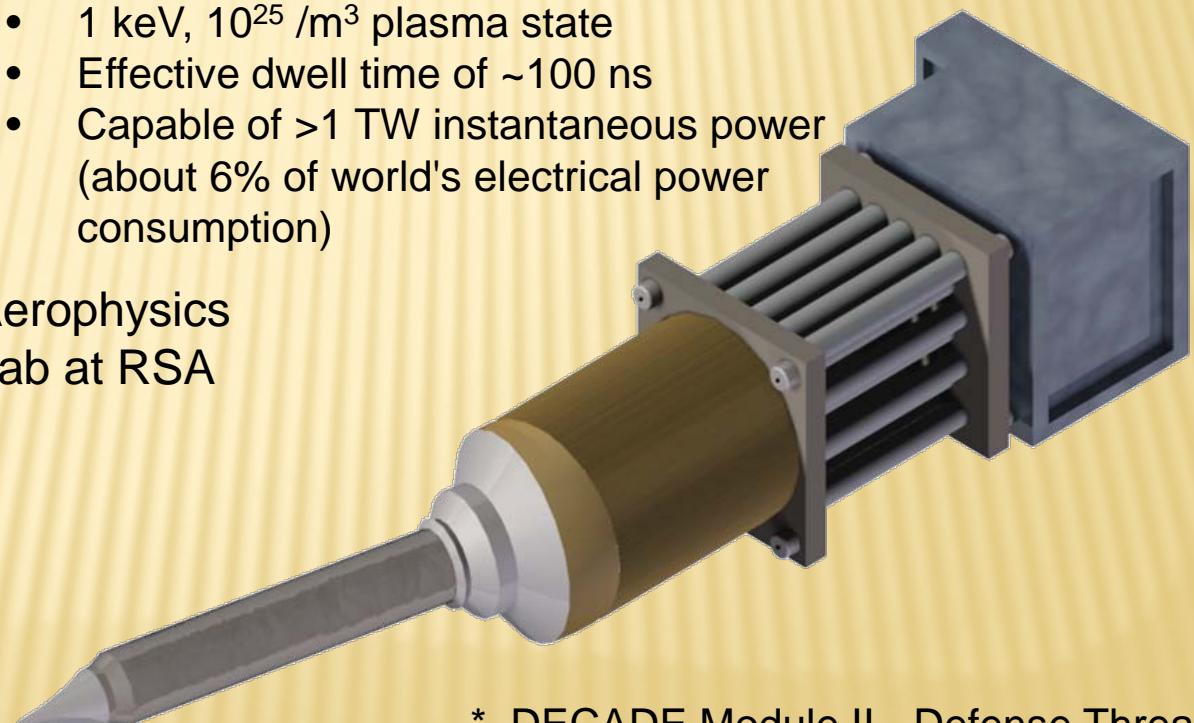
* DECADE Module II - Defense Threat Reduction Agency, circa 1995

Z-PINCH DM2 ASSEMBLY CONCEPT
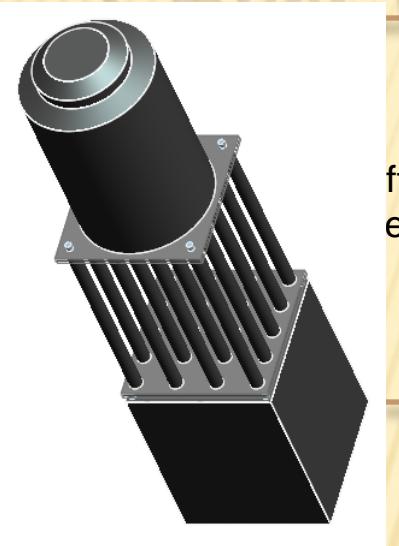
ft. (15.2 m)
erall Height

Single DM2
Capacitor
Module
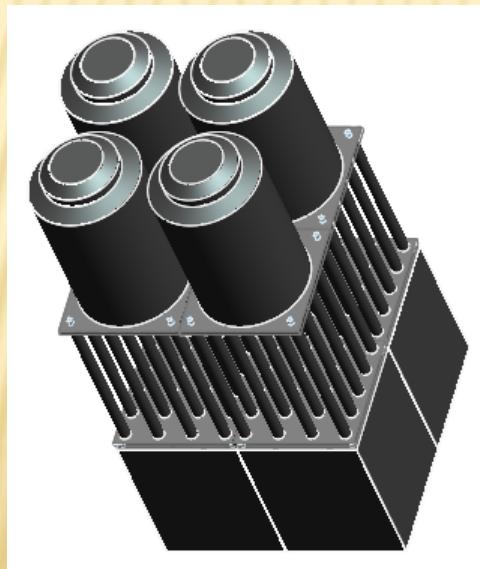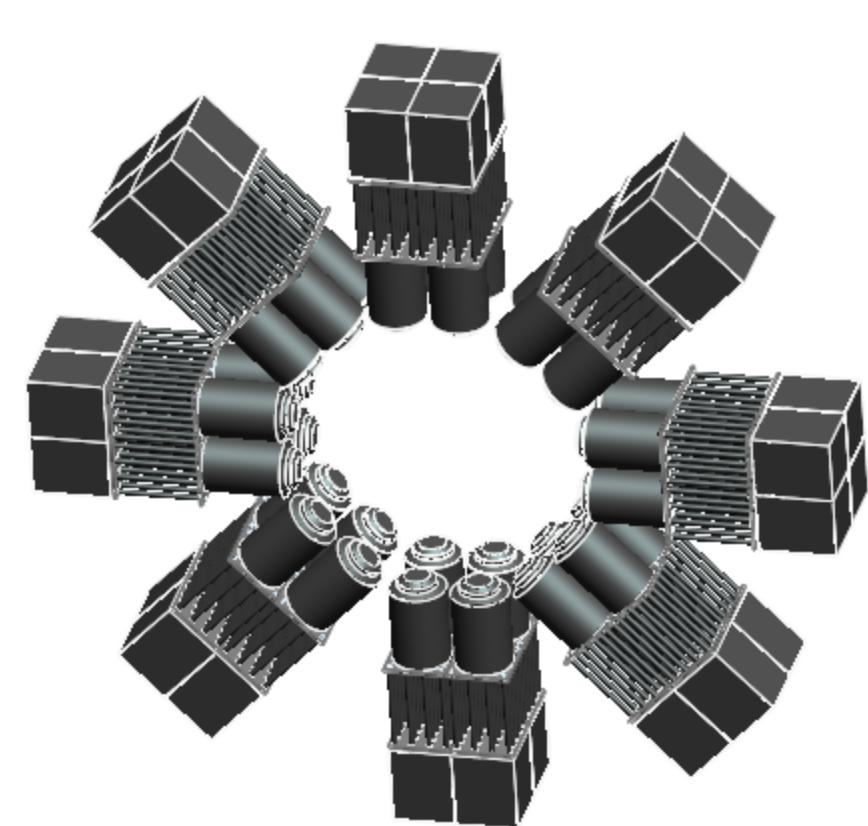
Four DM2 Modules

32 DM2 Modules

Charge transmission lines
not shown

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