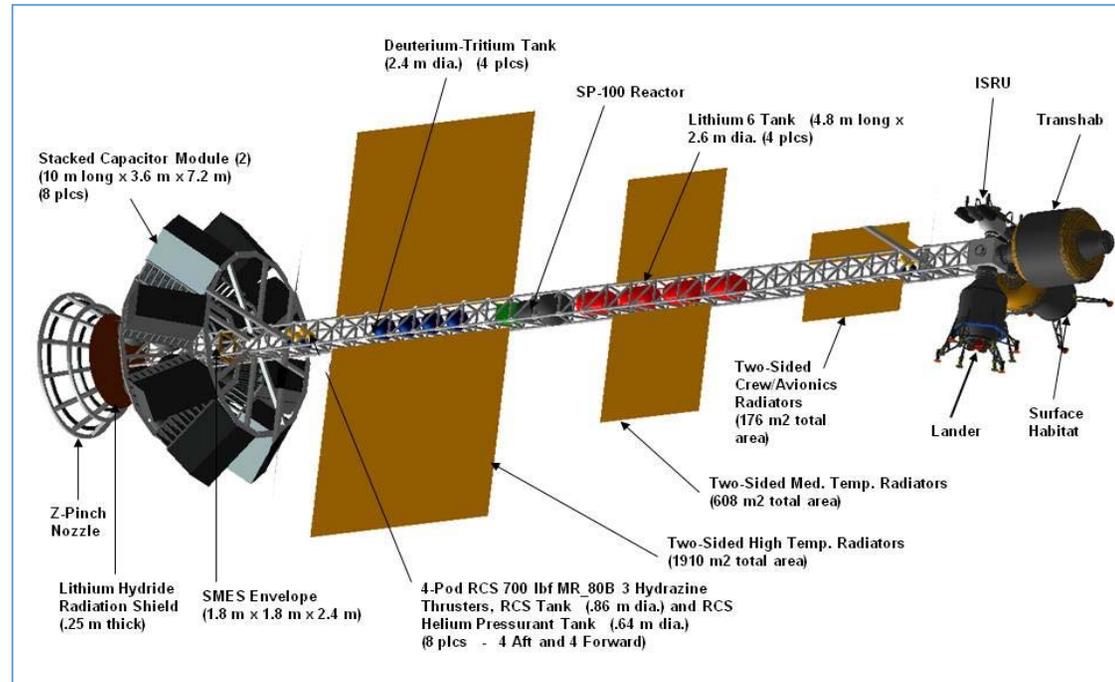
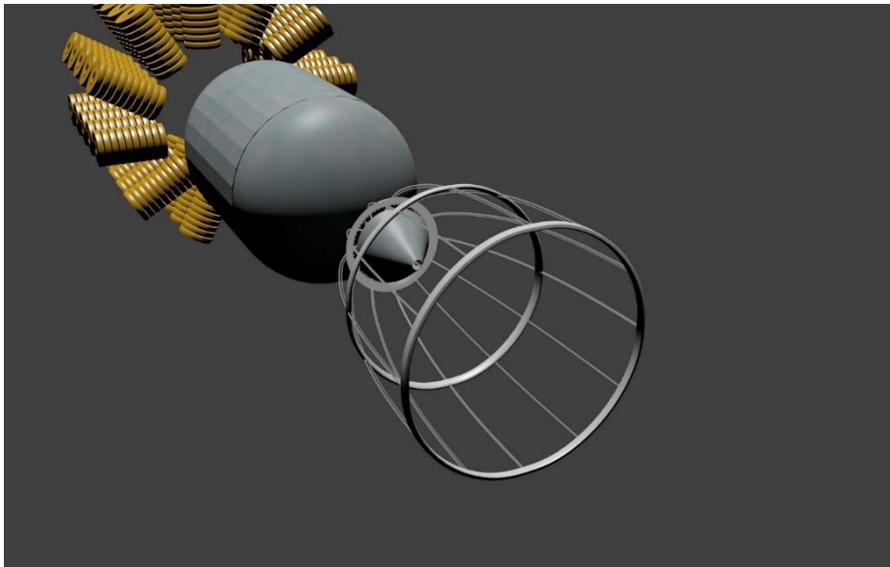


# Pulsed Fission Fusion (PuFF) Propulsion System



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## Teammates and Acknowledgements



- Current

- Jason Cassibry, Ph.D. – Associate Professor, UAH
- Glen Doughty, NASA-MSFC/ER24
- Brian Taylor, NASA-MSFC/ER23
- Patrick Giddens – Graduate Student, UAH
- Bill Seidler, Ph.D. – Research Professor, UAH
- Anthony DeCicco – University of Maryland
- Tyler Cowen – Columbia University

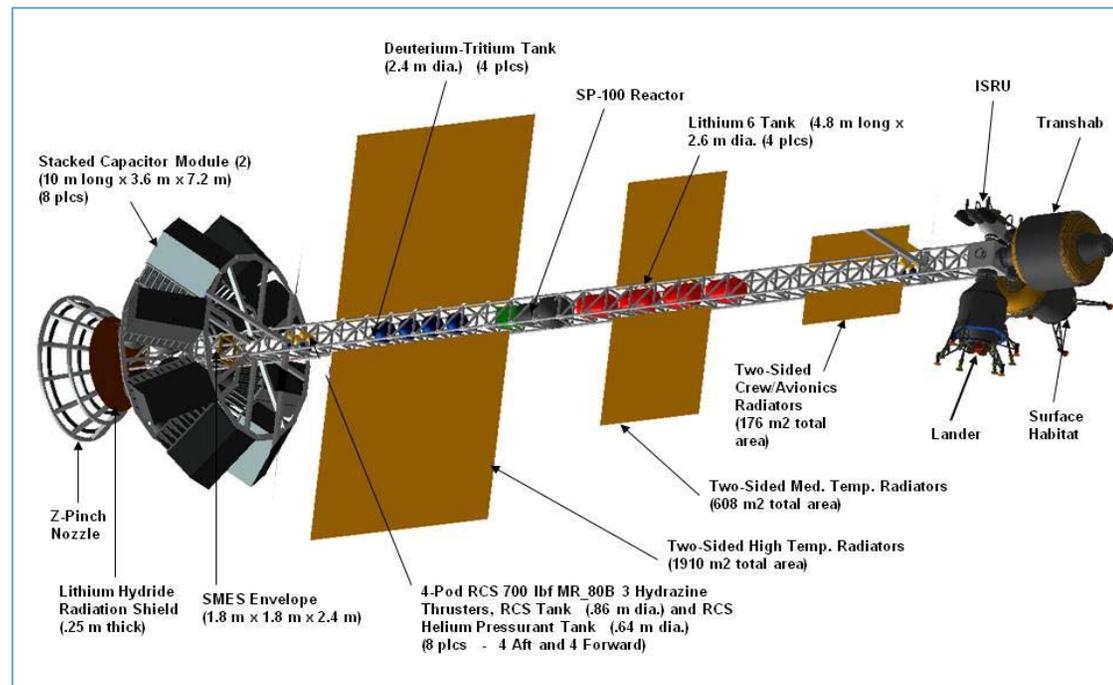
- Past

- Leo Fabisinski – Senior Engineer, ISSI
- David Bradley – Senior Engineer, Yetispace
- Erin Gish, Engineer – Boeing



## Pulsed Fission Fusion (PUFF) Propulsion System

- Propulsion concept with significant performance capability with potential to open the solar system for human exploration and near interstellar space for robotic probes
- Concept focus was toward a single design suitable to enabling wide range of missions. For Mars mission performance sufficient to carry Space Habitat, CEV, Lander, Surface Habitat and ISRU facility.
- Engine system provides a propulsive impulse operating on the principle of a pulsed two stage nuclear reaction triggered by the compression of a fuel target by means of an intense electrical pulse
- Resultant charged particles, emitted by the impulse, are deflected by magnetic nozzle, also serving as a energy capture device to energize the primary power system capacitors for subsequent pulse



Polsgrove, T. et al. Design of Z-Pinch and Dense Plasma Focus Powered Vehicles, 2010 AIAA Aerospace Sciences Meeting

## Two Stage Nuclear Reaction Sequence



- **Pre-reaction**

- Lithium (Li) shell/cone is injected to bridge the power system anode to target holder (providing a complete circuit)
- 2 mega-amperes (at 2 mega-volts) travels along the liquid lithium cone to target.
- Lorentz force ( $\vec{j} \times \vec{B}$ ) produced by the flowing current and generated magnetic field compresses hybrid target of uranium and Deuterium-Tritium (D-T) to 1/10 original size, reaching criticality for the Uranium.

- **First Stage (Fission)**

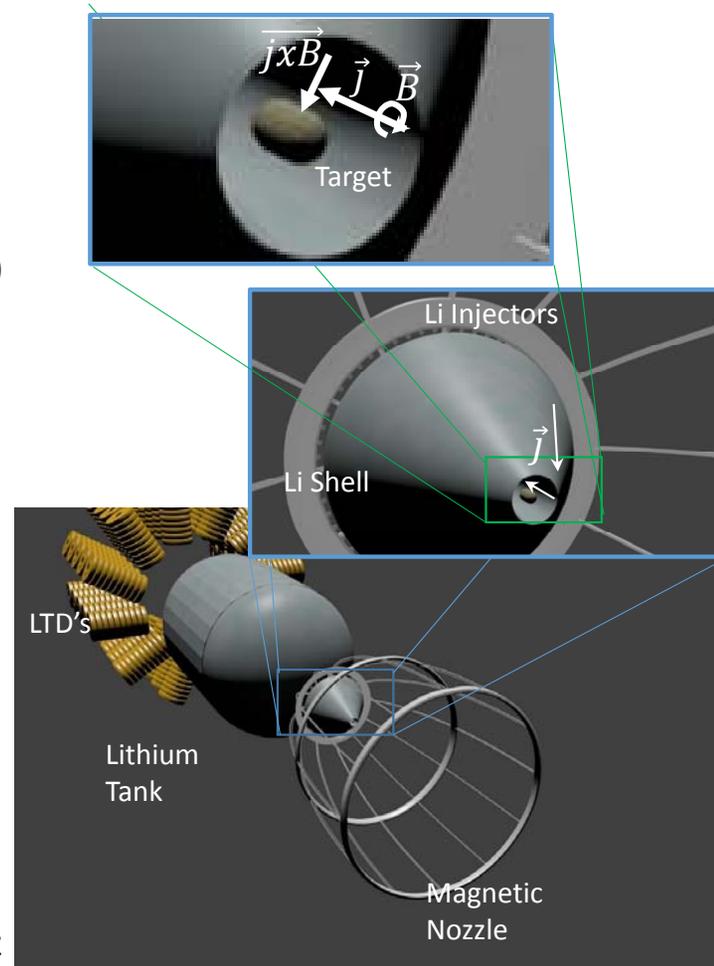
- Uranium criticality produces spontaneous fission reaction (heating)
- Fission heats the D-T fuel creating fusion conditions (interaction cross-section)

- **Second Stage (Fission - Fusion Cascade)**

- Fusion produces additional neutron which in turn ignites more fission
- Additional fission reactions generate more heat, boosting fusion rate
- Fission to D-T fusion cycle cascades until burnout.

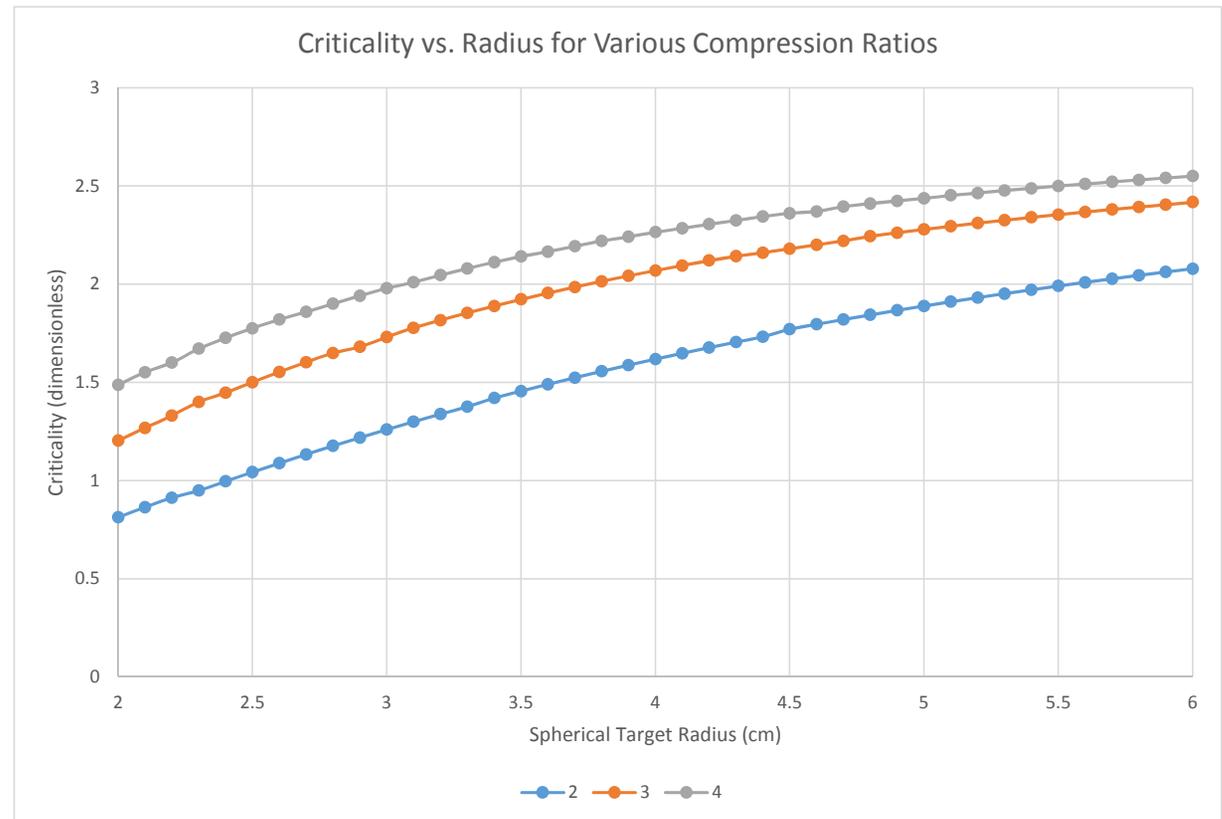
- **Expansion**

- Plasma produced during impulse expands outward against magnetic nozzle
- Magnetic nozzle directs the particles generating thrust & captures energy necessary to initiate the next pulse
- Single target impulse event requires several microseconds; repeat up to 100 Hz

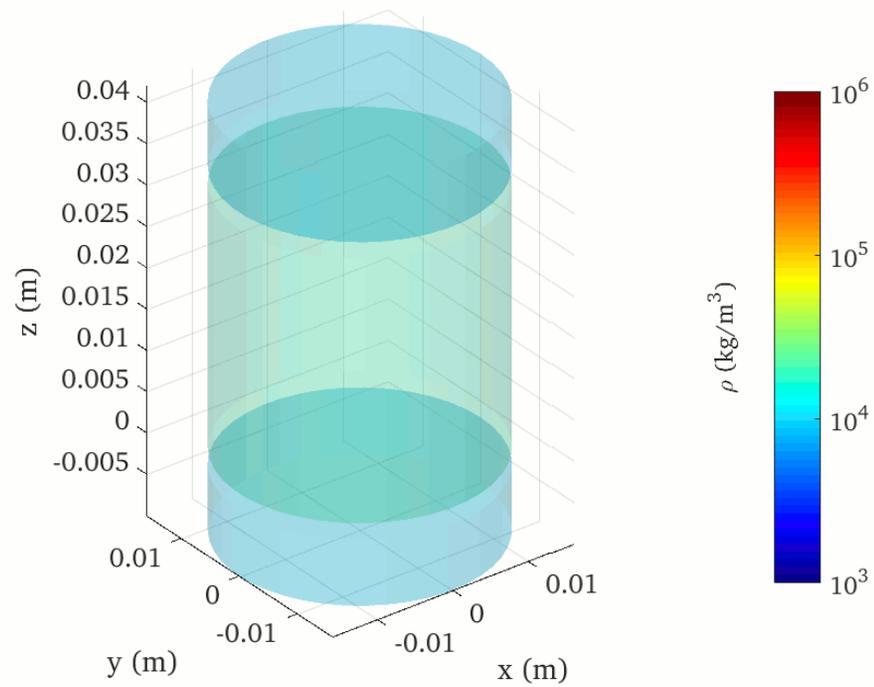


- **Dials for successful implosion:**

- **Target composition**
- **Target geometry**
- **Compression level**
- **Duration**
  - Instabilities
  - Energy release
  - Shock propagation
  - Starting neutron flux
- **Tamper geometry**



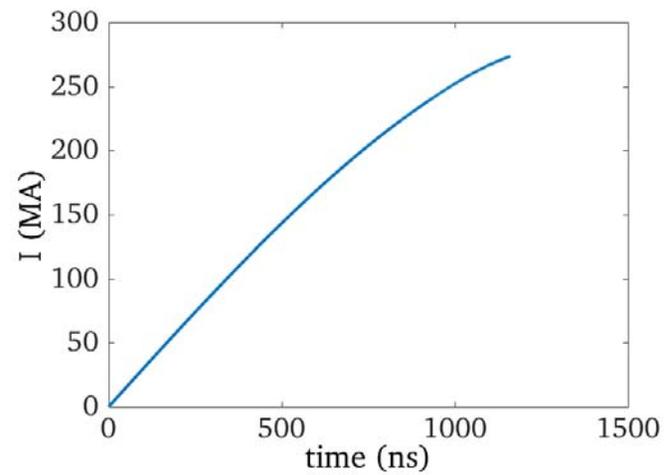
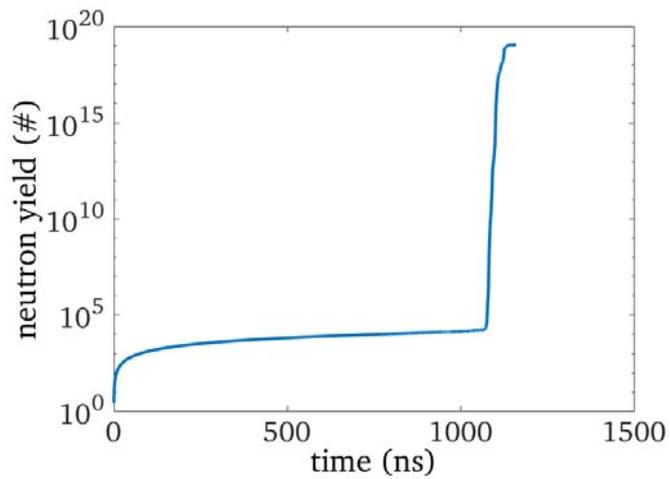
# Compression of Pure Solid Uranium Target with Pulsed Current



# Criticality



Target goes supercritical just after 1  $\mu\text{s}$  near a peak current of 270 MA. We will explore ways of lowering the required current in future work.





- Engine Performance

- Based on previous fusion designs
- Much analysis and experimentation to be made to lock down pulse frequency and target size
- Specific impulse and thrust are variable, can be modified by amount of lithium injected

Parameter	Value
Isp (vac)	20,000 sec
Thrust	29,400 N (6.5 klbf)
Specific Power	96 kW/kg
g's	0.015-0.027

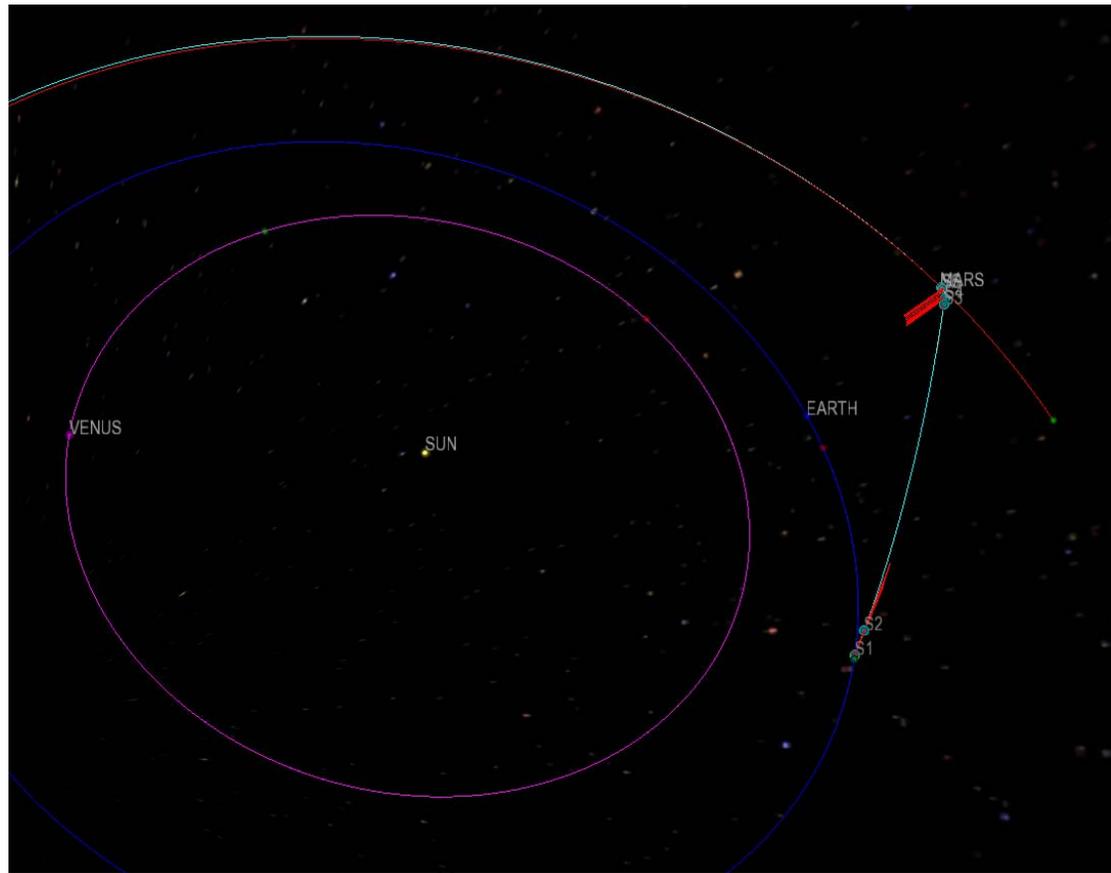
- Future Performance

- Introduction of LTD's can increase specific power by factor of 10

## Mars High Speed Mission



- Earth to Mars in 37 days
  - 0.6 Earth escape
  - 2.6 day TMI
  - 31.4 day coast
  - 0.8 day Mars deceleration
  - 2.1 day Mars capture
- Payload
  - 25 mT crew compartment

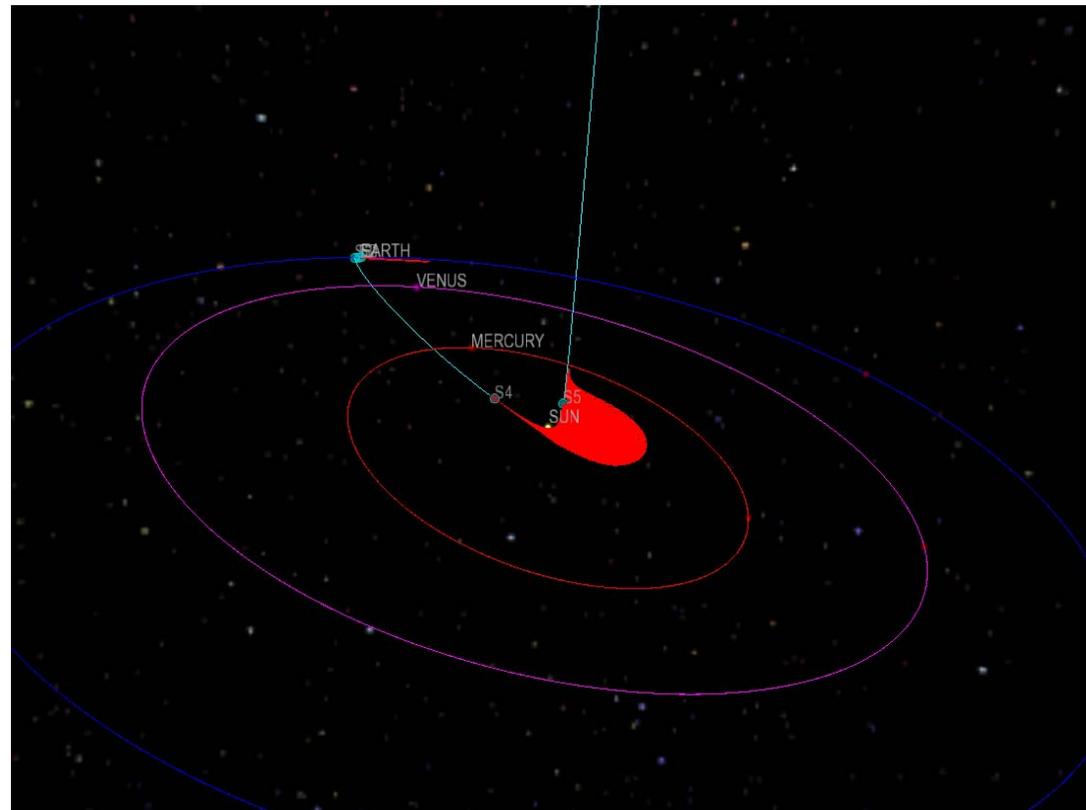


- Interstellar Space

- Termination shock in 5 years (pass Voyager I)
- 275 AU in 10 years
- Solar gravitational lens in 20 years
- 1000 AU in 36 years

- Burn profile

- 0.4 days Earth escape
- 1.4 days deorbit
- 48 day inbound coast
- 2.5 day solar burnout



## Mass Breakout



Subsystem	Mars Express	TAU Mission
Magnetic Nozzle	14.83 mT	14.83 mT
Radiation Shielding	14.01	14.01
D-T Tankage	5.0	5.0
Li Tankage	1.45	0.94
Truss	2.71	2.09
Other Primary Structures	0.64	0.49
Secondary Structures	0.13	0.10
Capacitor Banks	2.10	2.10
Marx Generator Circuitry	0.13	0.13
RCS Wet Mass	1.03	0.79
Low Temp Heat Rejection	1.30	1.30
Medium Temp Heat Rejection	14.82	14.82
High Temp Heat Rejection	1.26	1.26
LN2 Seed Coil Cooling	8.41	8.41
Auxiliary Power	4.40	4.40
Avionics	0.39	0.39
Payload	25.00	10.00
<b>Dry Mass (without MGL)</b>	<b>94.87</b>	<b>77.57</b>
Mass Growth Allowance (30%)	40.66	35.21
<b>Total Dry Mass</b>	<b>135.53</b>	<b>112.78</b>
Fuel	56.02	37.03
<b>Total Wet Mass</b>	<b>191.55</b>	<b>149.81</b>

# Activities Supporting Pulsed Fission Fusion (PuFF) Propulsion



Three primary areas of focus advanced basic research for PuFF concept.

- **Charger – 1 – UAH led program, NASA-MSFC and Boeing participation – High Power/Pulsed Power Facility - ONGOING**
  - A test facility for high power and thermonuclear fusion propulsion concepts, astrophysics modeling, radiation physics
  - Located in the UAH Aerophysics Lab at Redstone
  - The highest instantaneous pulsed power facility in academia – 572 kJ (1 TW at 100 ns) (1 MA at 1 MV)
  - Original equipment received from DTRA in 2012
  - **Resource to evaluate PuFF target underlying impulse physics**
- **Linear Transformer Drivers (LTD's) – Enabling Power System Component (Mass/Pulse) - ONGOING**
  - Originally developed in Russia, several purchased by DOE (Sandia Nat. Labs)
  - Ring of capacitors discharge into central ring, inducing current in conductors running through center
  - Much higher efficiency and mass savings relative to current Marx bank technology
  - Sandia baselining LTD's for next generation Z-machine (\$3-4 B national facility)
  - NASA-MSFC developing smaller versions for pulsed plasma propulsion use
  - Larger system concepts envisioned as flight weight option for PuFF
  - **Enabling technology significantly reduces mass of overall vehicle**



## Charger - 1

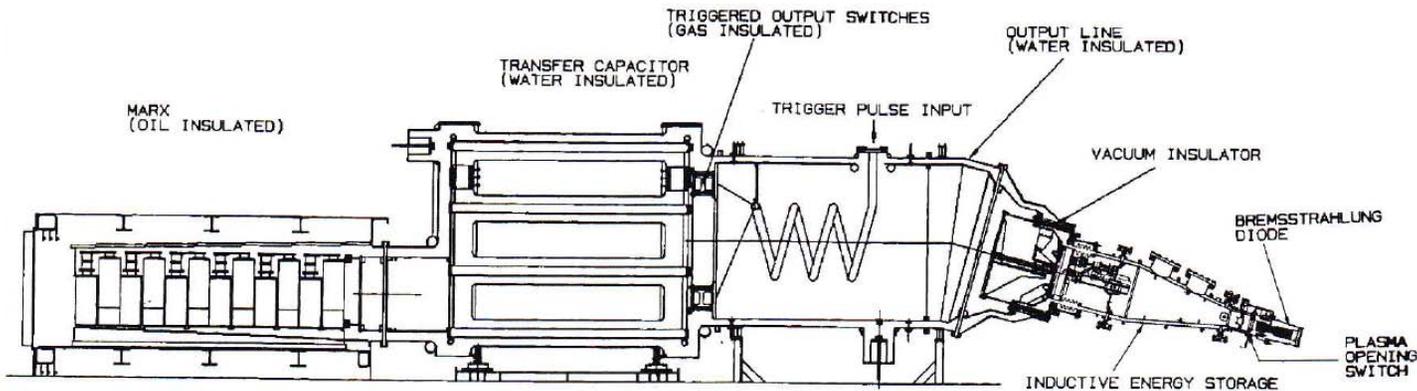
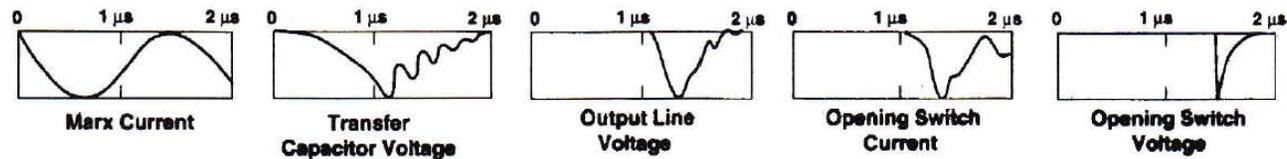
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## How Charger – 1 Works



- Successive systems compress and intensify pulse
  - 1.2 MV @ 1 MA



## Marx Bank



- Full power: charged to  $\pm 85$  kV
- Aerovox capacitors,  $C = 2.2 \mu\text{F}$ , rated at 100 kV
- Once triggered, erected Marx looks more or less like a single capacitor with value  $1.1 \mu\text{F}$ , charged to 1.02 MV
- **Total stored energy: 572 kJ**



## Transfer Capacitor



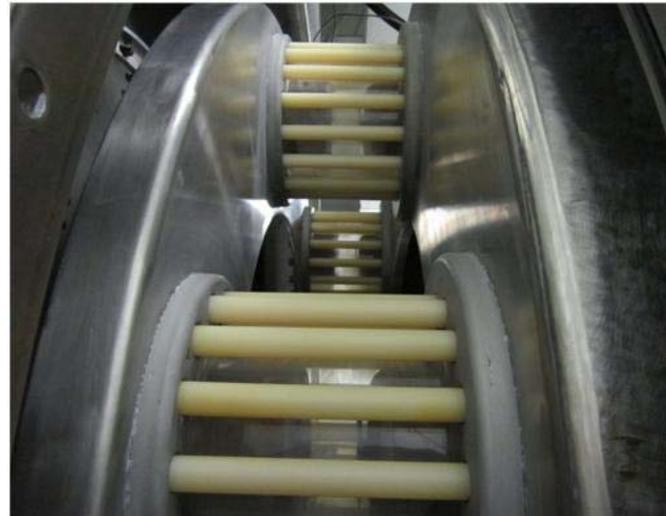
- Collection of 32 coaxial lines bussed together on either end
- Water filled
- Urethane diaphragm that separates oil in Marx tank from water in the TC
- Total capacitance  $C = 0.43 \mu\text{F}$ , or less than half the effective capacitance of the Marx
- Divertor switches located on both upstream and downstream ends of TC
  - Designed to remove 320 kJ ASAP after forward pulse has passed (just after first zero-crossing)



## Output Line Switches



- 6 switches control output from TC: these switches are fired simultaneously and are in parallel to share the output current equally
  - Pressurized with SF<sub>6</sub> to ~90 psig (variable depending on test)
  - Last triggered stage in pulsed power system
  - Peak voltage on switches: 1.2-1.4 MV
  - Total current carried: 1.6-1.8 MA
  
- Jitter in the firing of output switches is ~2-3 ns leading to an overall jitter in the arrival time of the current at the front end of 4-5 ns



## Output Line

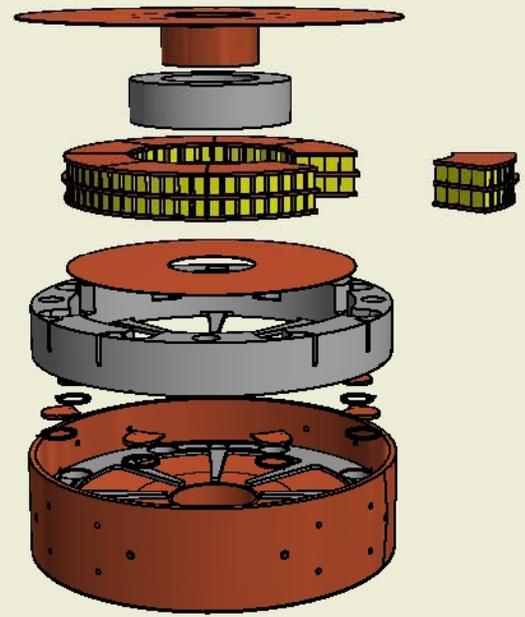
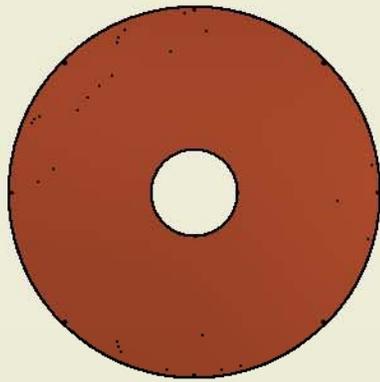


- Single line has impedance  $Z \sim 0.5 \Omega$  and is 100 ns long
- Total insulator stack height is 35 cm
  - This design requires cleaning of the insulator surface after 20-30 full power discharges
- At the end of the water OL is an oil section isolated on the upstream side from water by a 1 inch thick polyurethane diaphragm and isolated on the downstream side from the vacuum components by a 16 gradient ring, polyurethane and Dendresist, high voltage insulator (see picture)

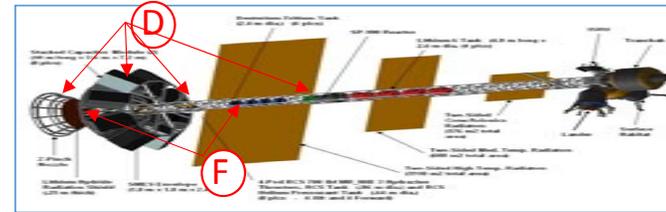
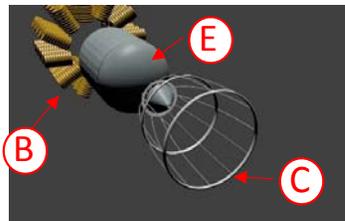
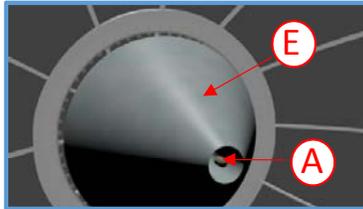




LTD Version 7



# Key Technologies – Progression from Physics to Engineering



	A - Target	B - Linear Transformer Drivers (LTD)	C - Magnetic Nozzle (MN)	D – Recharge System	E – Lithium Injectors	F - Target Storage / Dispenser
	<b>Implosion Capsule</b>	<b>Pulsed power storage, discharge and compression system</b>	<b>Directs fission/fusion products and recovers energy for next pulse</b>	<b>Pulse generation and onboard power storage/generation</b>	<b>Lithium tankage / distribution systems to provide target liner and power conduction path</b>	<b>Maintains targets in non-critical configuration, injects into nozzle</b>
	Implosion Physics, instabilities and burn-up	Physics of LTD super-cavity operation, power density and pulse compression	High temperature magnetic nozzle topology, field strength, plasma coupling	Power system topology to couple MN coupled energy recovery to LTD array	Linear physics interaction with implosion and power system	Vessel /internal dispensing hardware design
	Target detailed design, enrichment and containment	LTD system material and component science to meet energy requirements	Power recovery approach methodology and design to maximize efficiency	Power system topology to process LTD energy for Liner/target implosion	Vessel/internal heating design for solid material storage - liquid dispensing	Target loading and containment protection
	Target burn-up/yield (model/experiment)	Performance physics of integrated multiple super-cavities to yield necessary pulse with and timing	Superconductor type and design for minimal cooling and cooling requirements/ subsystems	Onboard power generation to provide initial start / restart capability of system (solar/nuclear)	Liquid lithium feed system with pumps supplying implosion site	Feed tube(s) / conveyance design for dispensing to implosion location(s)
	Manufacturing approach for Target Quantities	LTD Manufacturing approaches and hardware integration	Magnet integrated cooling and operations control system	Integrated design and power balance incorporating subsystems	Liquid lithium liner generator design and testing	Target holding design at use location suitable for multi pulse operations
	Handling and Storage limitations & restrictions	Power / Liner system integration with structure to conduct energy pulse	Manufacture approach and integration technique with power systems	Manufacturing approach/ methodology for high power components	Liner recovery process and demo between pulses	

Maturation

Physics / R&D

Engineering