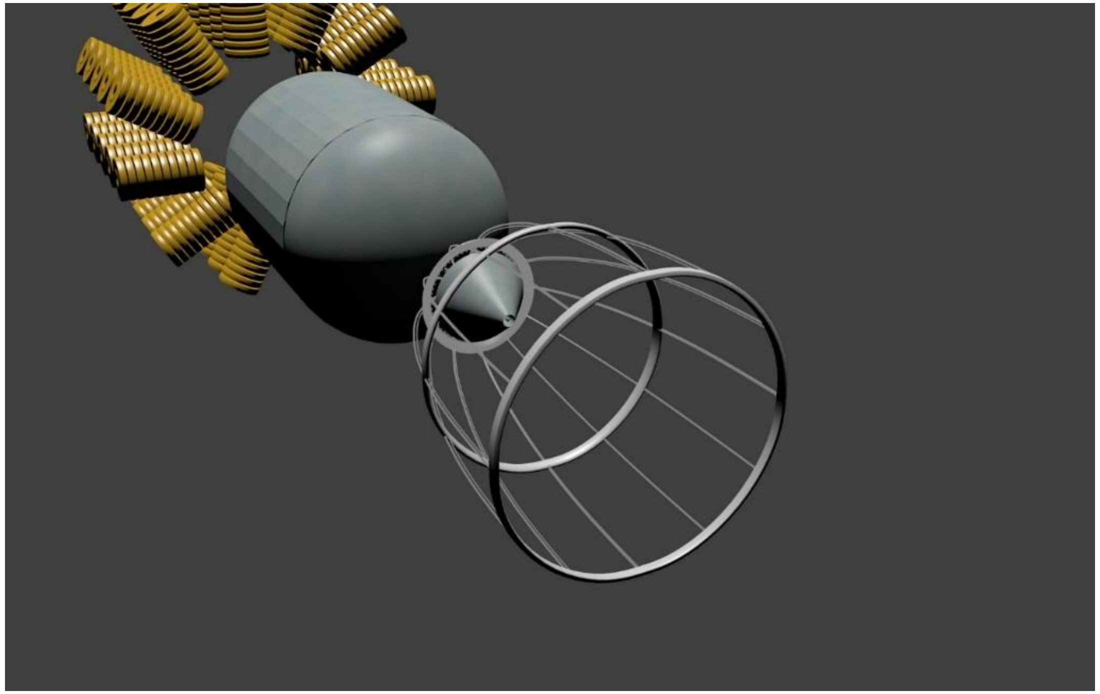
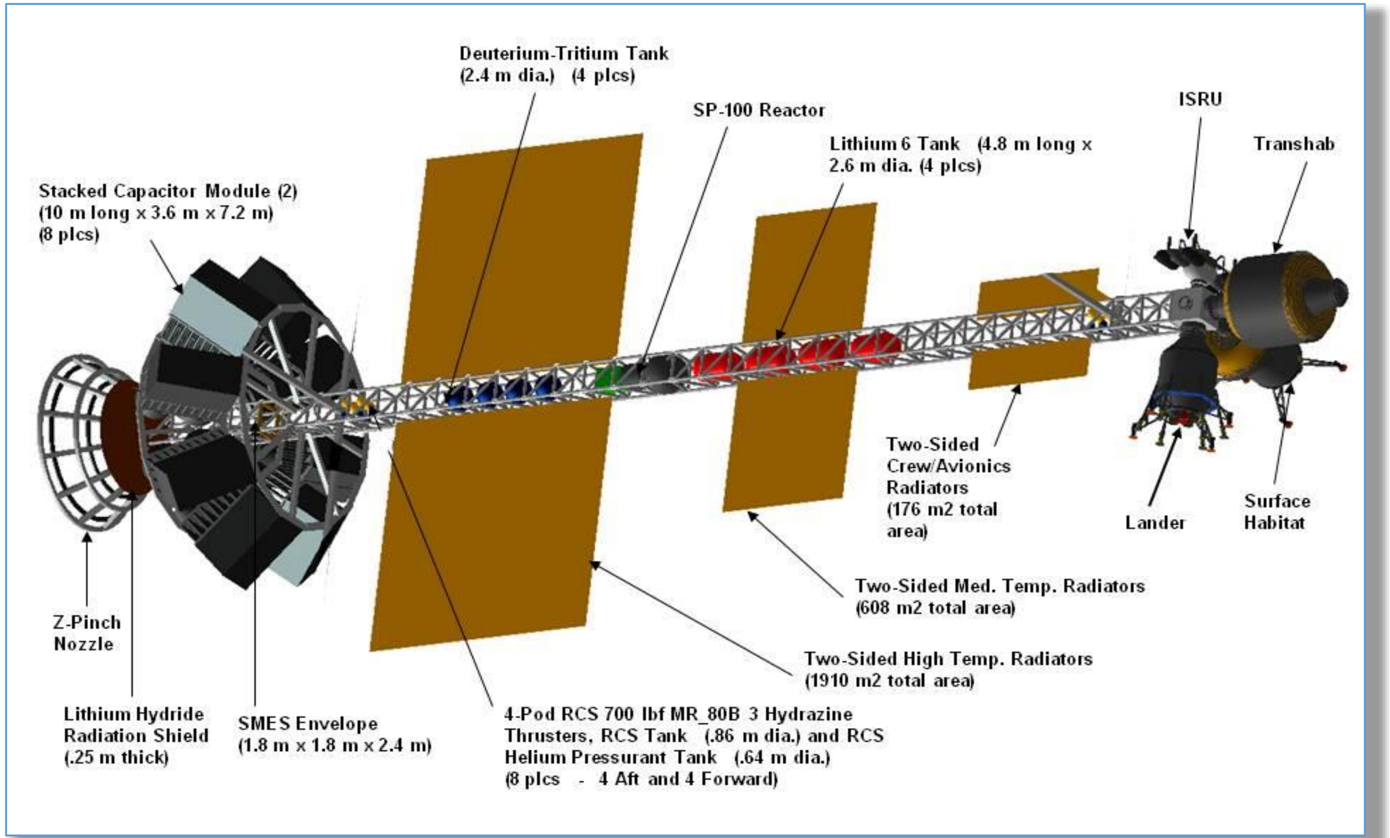
Pulsed Fission Fusion (PuFF) Propulsion System

Project PI: Robert B. Adams, Ph.D.





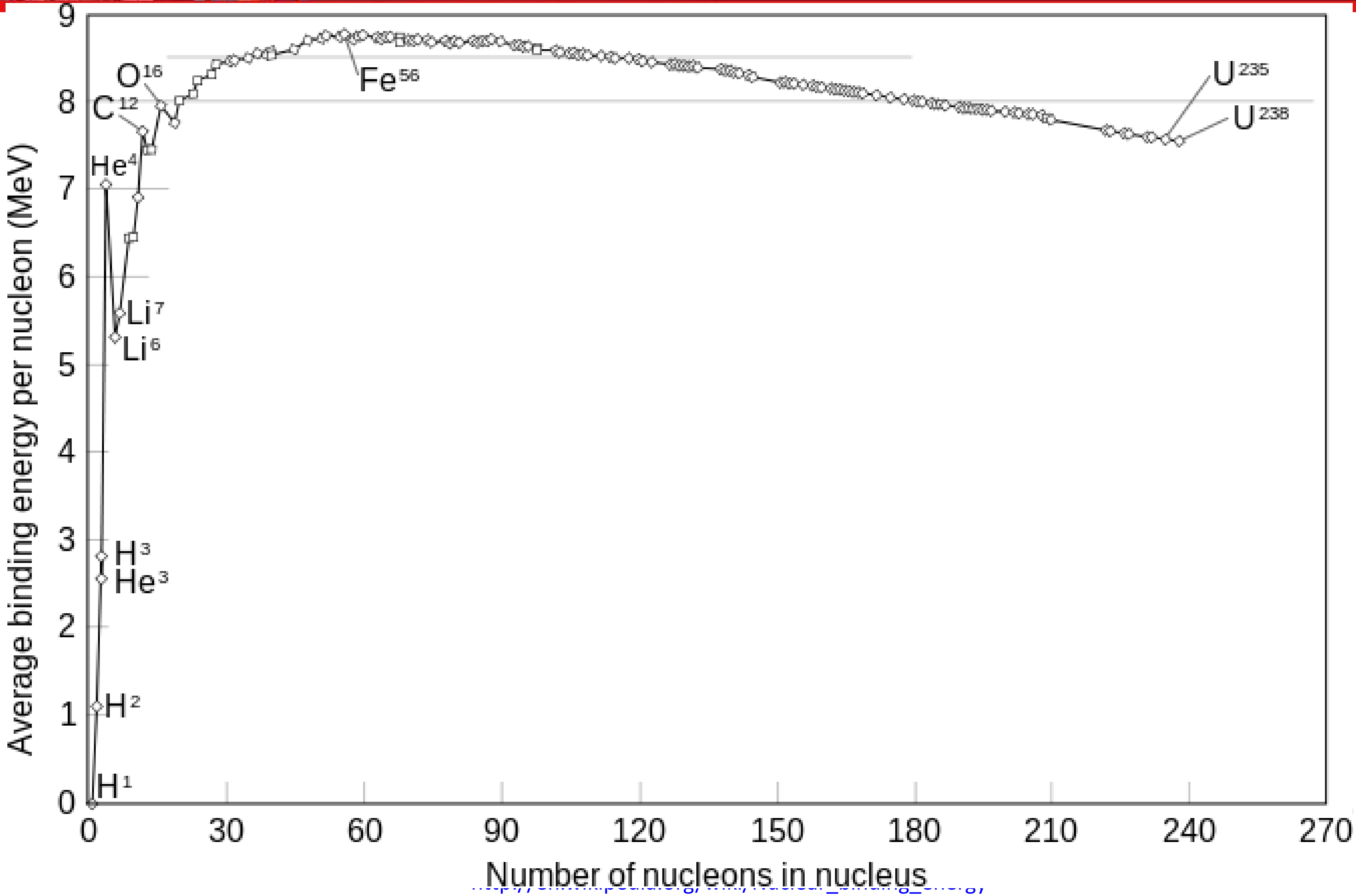
Teammates and Acknowledgements

Project PI: Robert B. Adams, Ph.D.

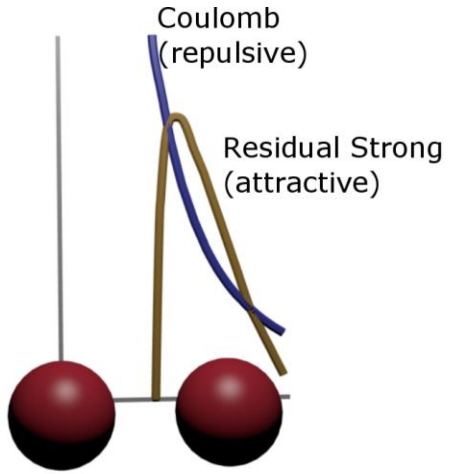
- Current
  - Jason Cassibry, Ph.D. – Associate Professor, UAH
  - Glen Doughty, NASA-MSFC/ER24
  - Brian Taylor, NASA-MSFC/ER23
  - Patrick Giddens – Graduate Student, UAH
  - Bill Seidler, Ph.D. – Research Professor, UAH
- Past
  - Leo Fabisinski – Senior Engineer, ISSI
  - David Bradley – Senior Engineer, Yetispace
  - Erin Gish, Engineer – Boeing

Fission and Fusion Energy Release

Project PI: Robert B. Adams, Ph.D.



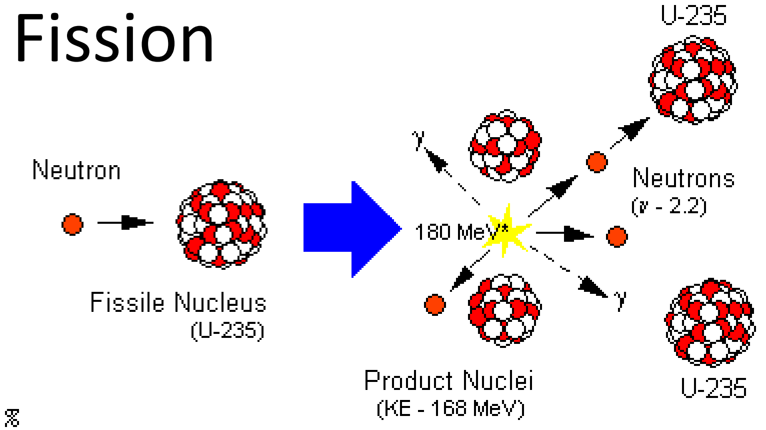
$$E=mc^2$$

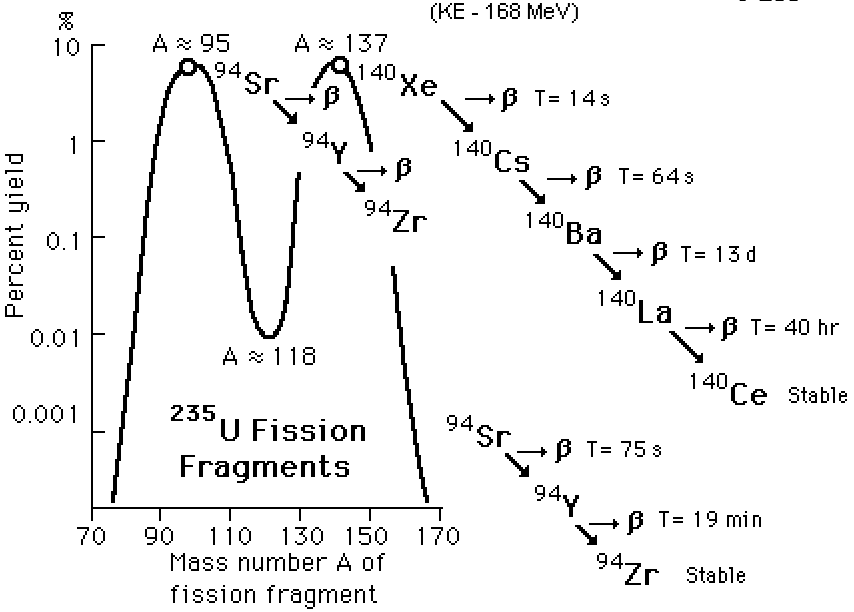


Fission/Fusion Reaction Space

Project PI: Robert B. Adams, Ph.D.

- Fission

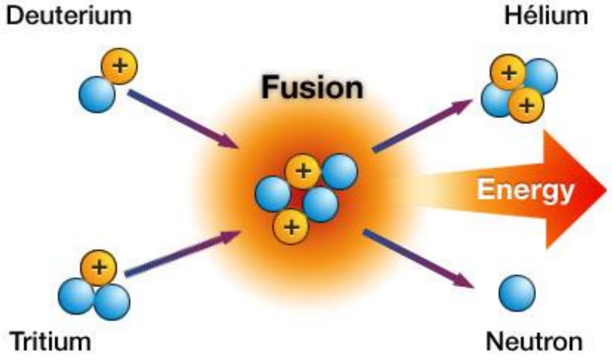




http://www.propagation.gatech.edu/ECE6390/project/Fall2010/Projects/group10/MANTIS_2010_SatCom/MANTIS_2010_SatCom/PowerSys/default.html

http://www.mwit.ac.th/~physicslab/hbase/nucene/fisfrag.html#c1

- Fusion

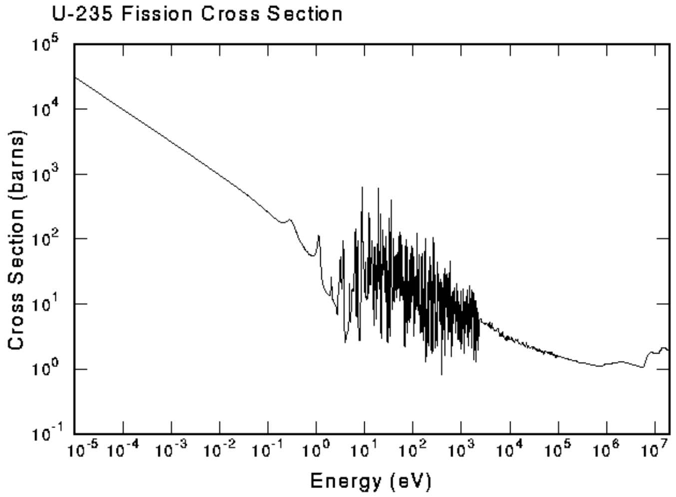


(1)	${}^{2}_{1}D + {}^{3}_{1}T \rightarrow {}^{4}_{2}He$ (3.5 MeV) $+ n^{0}$ (14.1 MeV)	
(2i)	${}^{2}_{1}D + {}^{2}_{1}D \rightarrow {}^{3}_{1}T$ (1.01 MeV) $+ p^{+}$ (3.02 MeV)	50%
(2ii)	$\rightarrow {}^{3}_{2}He$ (0.82 MeV) $+ n^{0}$ (2.45 MeV)	50%
(3)	${}^{2}_{1}D + {}^{3}_{2}He \rightarrow {}^{4}_{2}He$ (3.6 MeV) $+ p^{+}$ (14.7 MeV)	
(4)	${}^{3}_{1}T + {}^{3}_{1}T \rightarrow {}^{4}_{2}He + 2\,n^{0}$ + 11.3 MeV	
(5)	${}^{3}_{2}He + {}^{3}_{2}He \rightarrow {}^{4}_{2}He + 2\,p^{+}$ + 12.9 MeV	
(6i)	${}^{3}_{2}He + {}^{3}_{1}T \rightarrow {}^{4}_{2}He + p^{+} + n^{0}$ + 12.1 MeV	57%
(6ii)	$\rightarrow {}^{4}_{2}He$ (4.8 MeV) $+ {}^{2}_{1}D$ (9.5 MeV)	43%
(7i)	${}^{2}_{1}D + {}^{6}_{3}Li \rightarrow 2\,{}^{4}_{2}He$ + 22.4 MeV	
(7ii)	$\rightarrow {}^{3}_{2}He + {}^{4}_{2}He + n^{0}$ + 2.56 MeV	
(7iii)	$\rightarrow {}^{7}_{3}Li + p^{+}$ + 5.0 MeV	
(7iv)	$\rightarrow {}^{7}_{4}Be + n^{0}$ + 3.4 MeV	
(8)	$p^{+} + {}^{6}_{3}Li \rightarrow {}^{4}_{2}He$ (1.7 MeV) $+ {}^{3}_{2}He$ (2.3 MeV)	
(9)	${}^{3}_{2}He + {}^{6}_{3}Li \rightarrow 2\,{}^{4}_{2}He + p^{+}$ + 16.9 MeV	
(10)	$p^{+} + {}^{11}_{5}B \rightarrow 3\,{}^{4}_{2}He$ + 8.7 MeV	

http://fusionforenergy.europa.eu/understandingfusion/

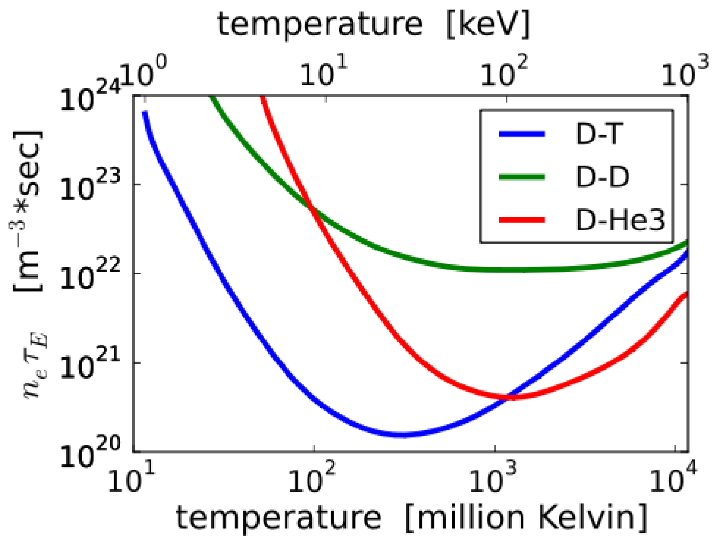
http://en.wikipedia.org/wiki/Nuclear_fusion

- Fission
  - Criticality is a function of
    - fission cross section
    - Number density
    - And geometry
  - Neutrons must balance
    - Lost outside reactor
    - Absorbed through photon



http://t2.lanl.gov/nis/tour/sch002.html

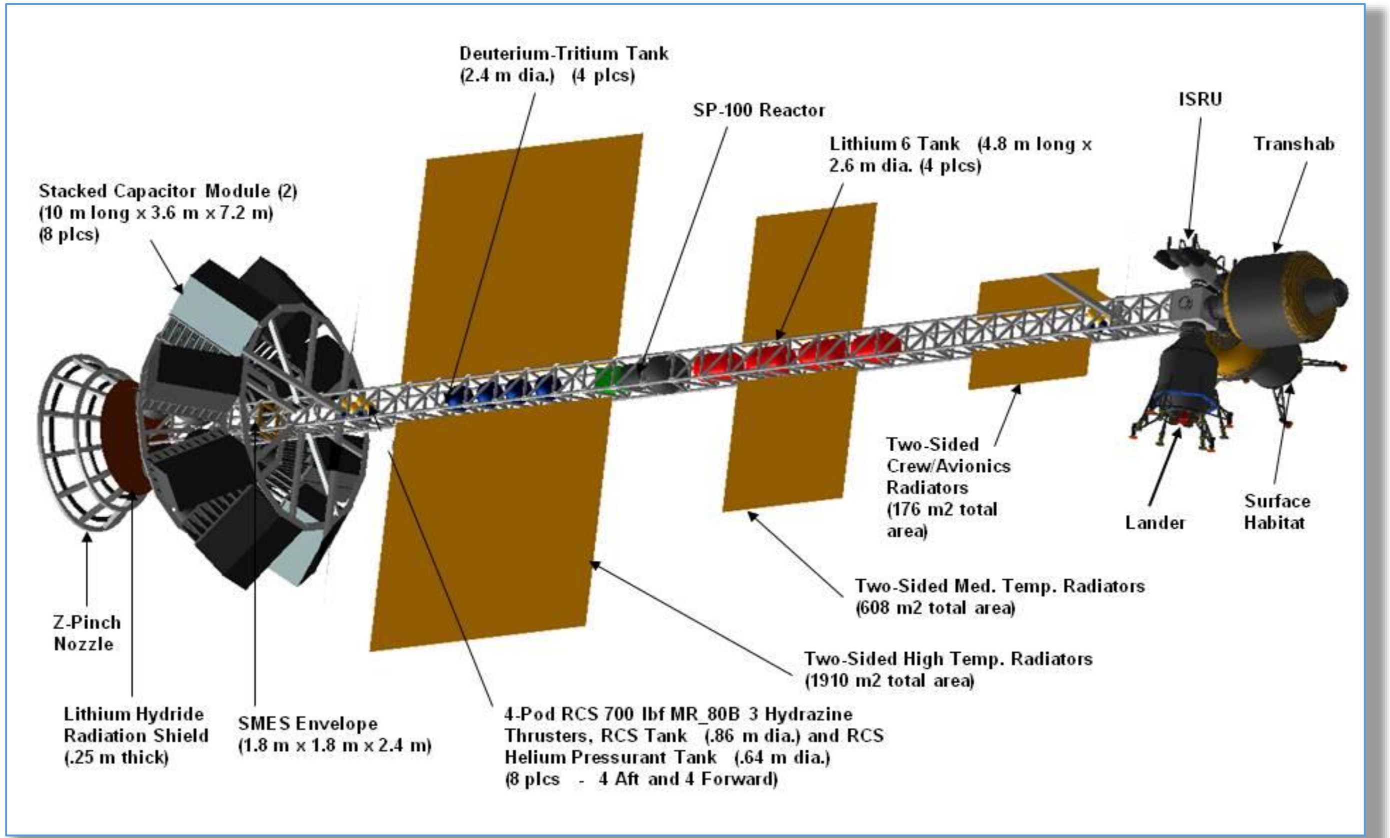
- Fusion
  - Breakeven is a function of
    - Fusion cross section
    - temperature distribution
    - density
  - Lawson Criterion



http://en.wikipedia.org/wiki/Lawson_criterion

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

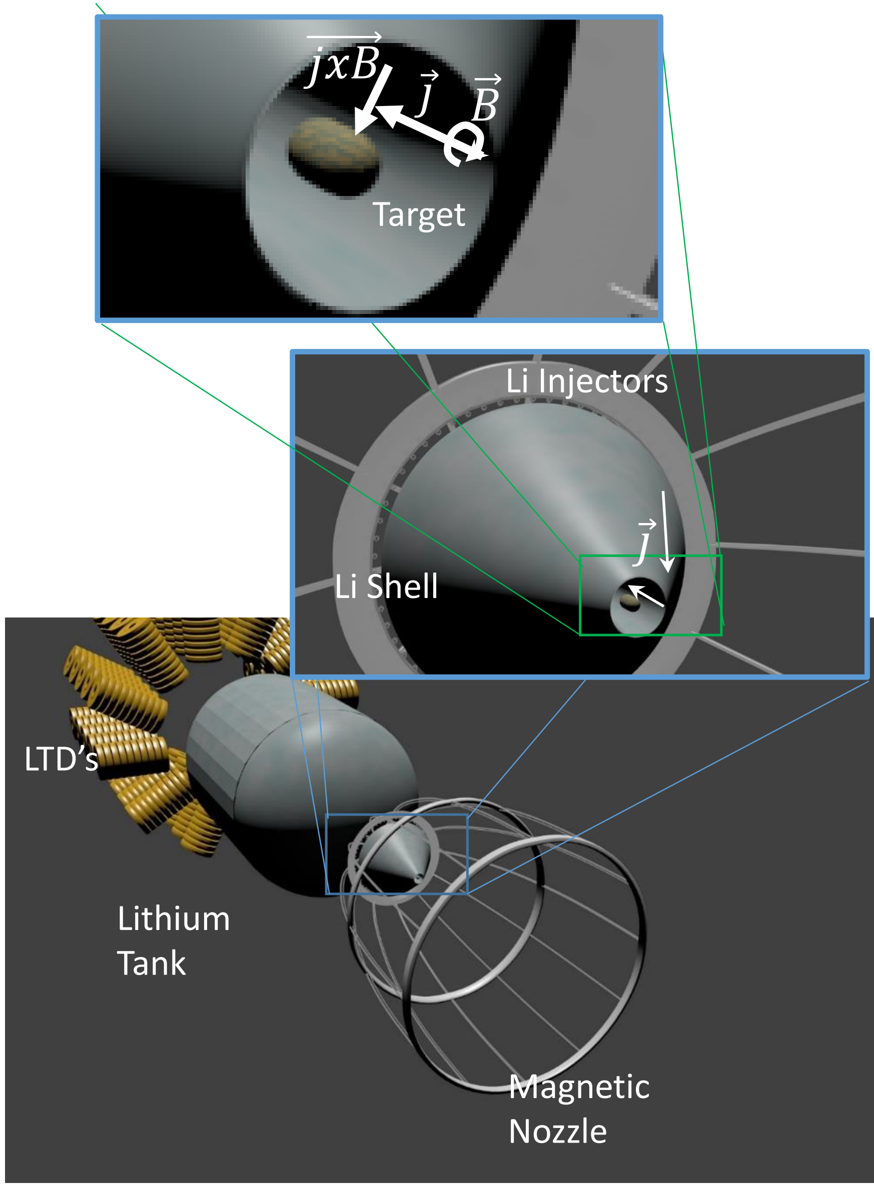


Polsgrove, T. et al. Design of Z-Pinch and Dense Plasma Focus Powered Vehicles, 2010 AIAA Aerospace Sciences Meeting

Two Stage Nuclear Reaction Sequence

Project PI: Robert B. Adams, Ph.D.

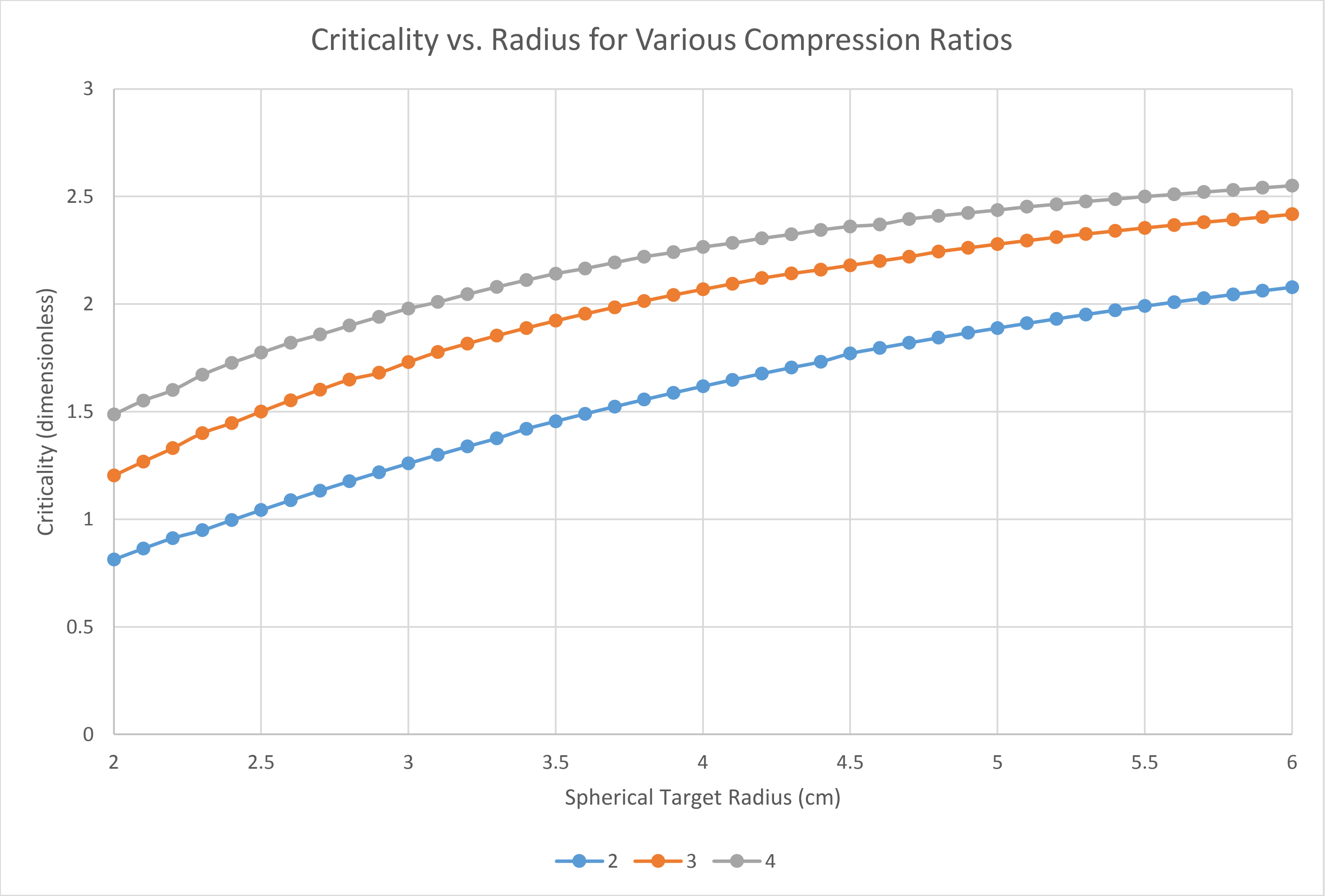
- ***Pre-reaction***
  - Lithium (Li) shell/cone is injected to bridge the power system anode to target holder (providing a complete circuit)
  - 2 mega-amps (at 2 mega-volts) travels along the liquid lithium cone to target.
  - Lorentz force (jxB) produced by the flowing current and generated magnetic 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 ignite 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



Criticality

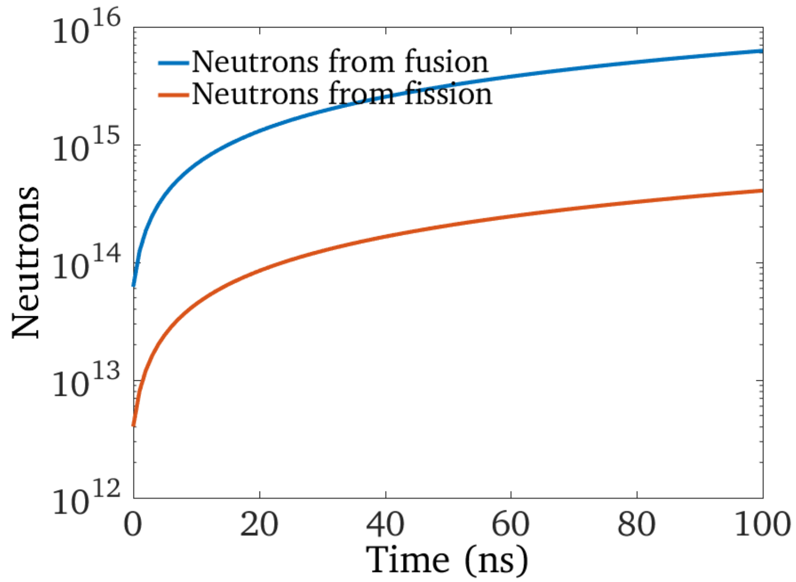
Project PI: Robert B. Adams, Ph.D.

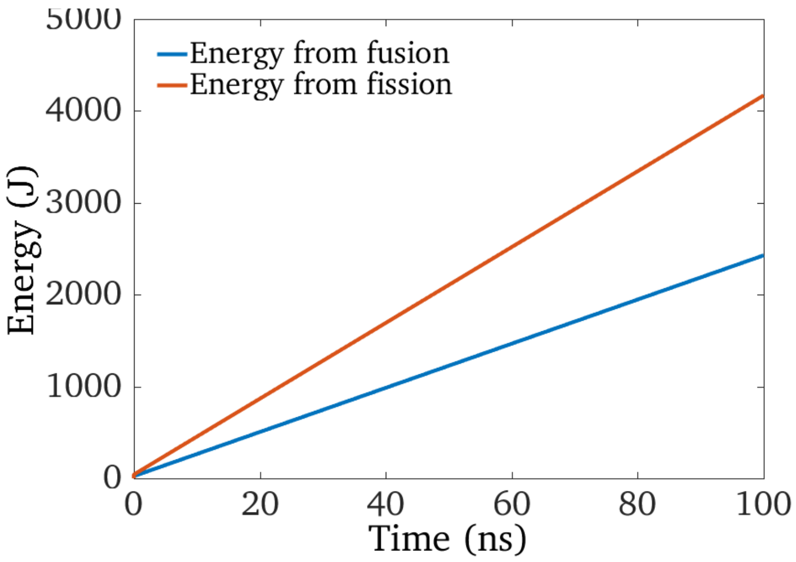
- ***Dials for successful implosion:***
  - ***Target composition***
  - ***Target geometry***
  - ***Compression level***
  - ***Duration***
    - Instabilities
    - Energy release
    - Shock propagation
    - Starting neutron flux
  - ***Tamper geometry***

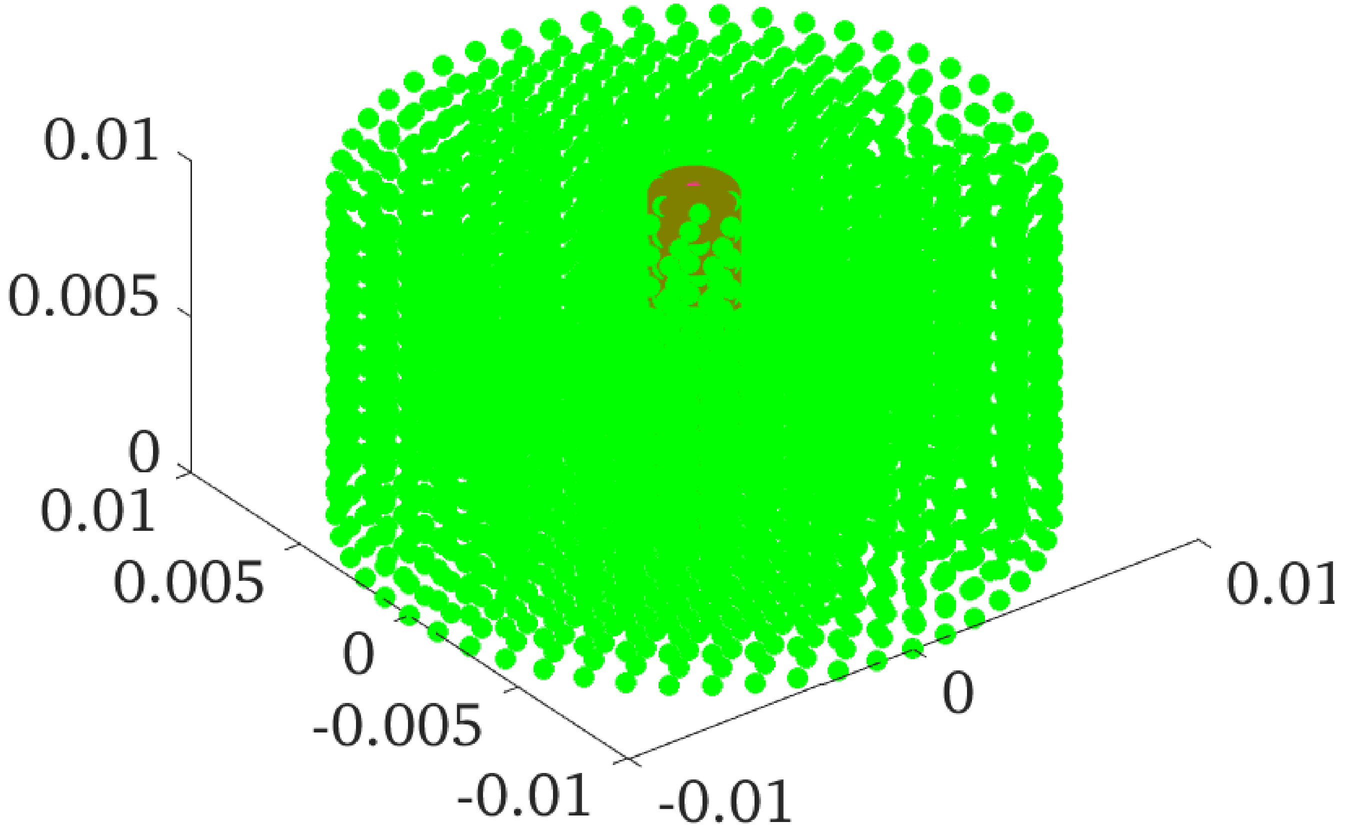


SPFMax

Project PI: Robert B. Adams, Ph.D.



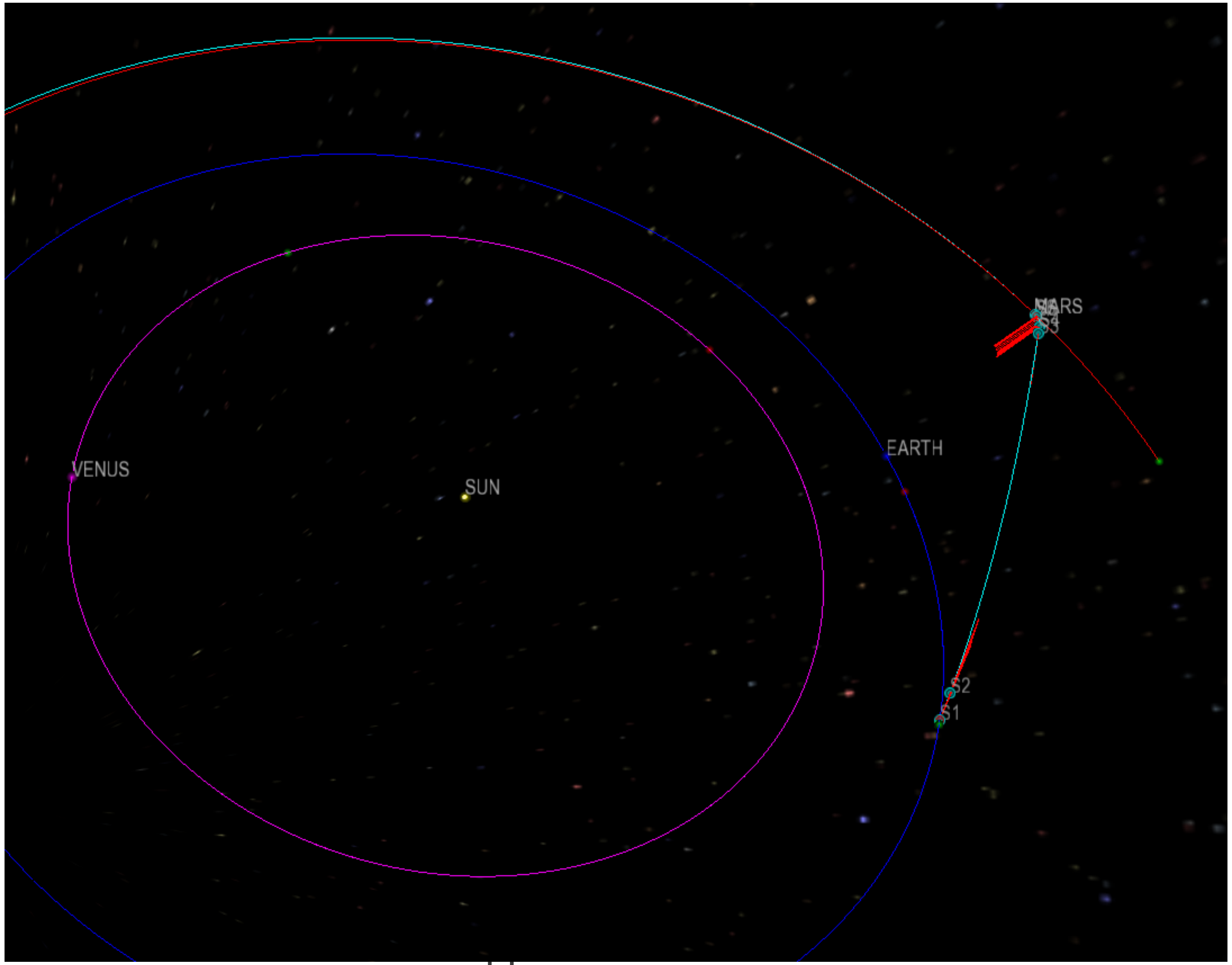




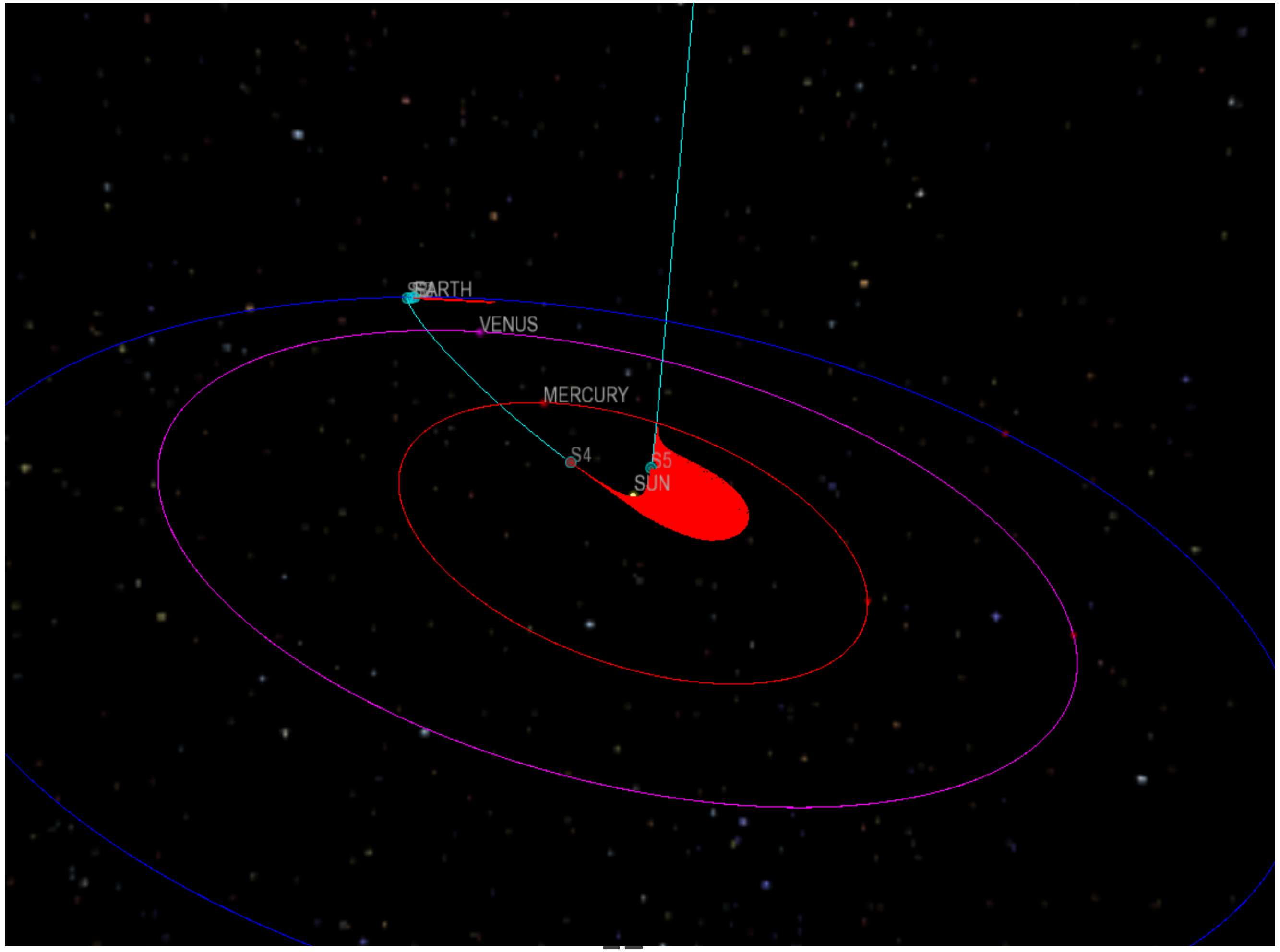
- Engine Performance
  - Based on previous fusion designs
  - Much analysis and experimentation to be made to lock down pulse frequency and target size
  - Specific impulse and thrust are variable, can be modified by amount of lithium injected
- Future Performance
  - Introduction of LTD's can increase specific power by factor of 10

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

- 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

Project PI: Robert B. Adams, Ph.D.

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
Dry Mass (without MGL)	**94.87**	**77.57**
Mass Growth Allowance (30%)	40.66	35.21
Total Dry Mass	**135.53**	**112.78**
Fuel	56.02	37.03
Total Wet Mass	***191.55***	***149.81***

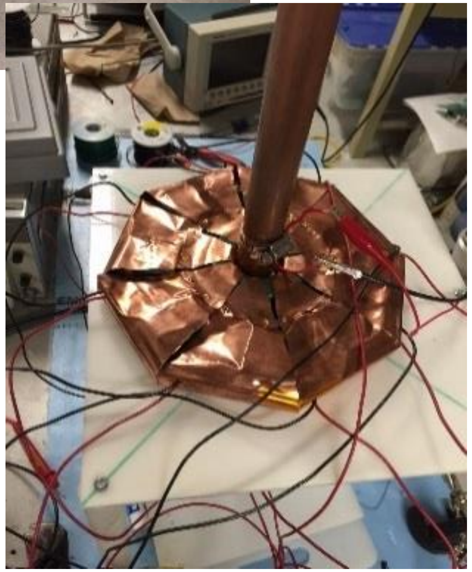
Activities Supporting Pulsed Fission Fusion (PuFF) Propulsion

Project PI: Robert B. Adams, Ph.D.

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

Project PI: Robert B. Adams, Ph.D.

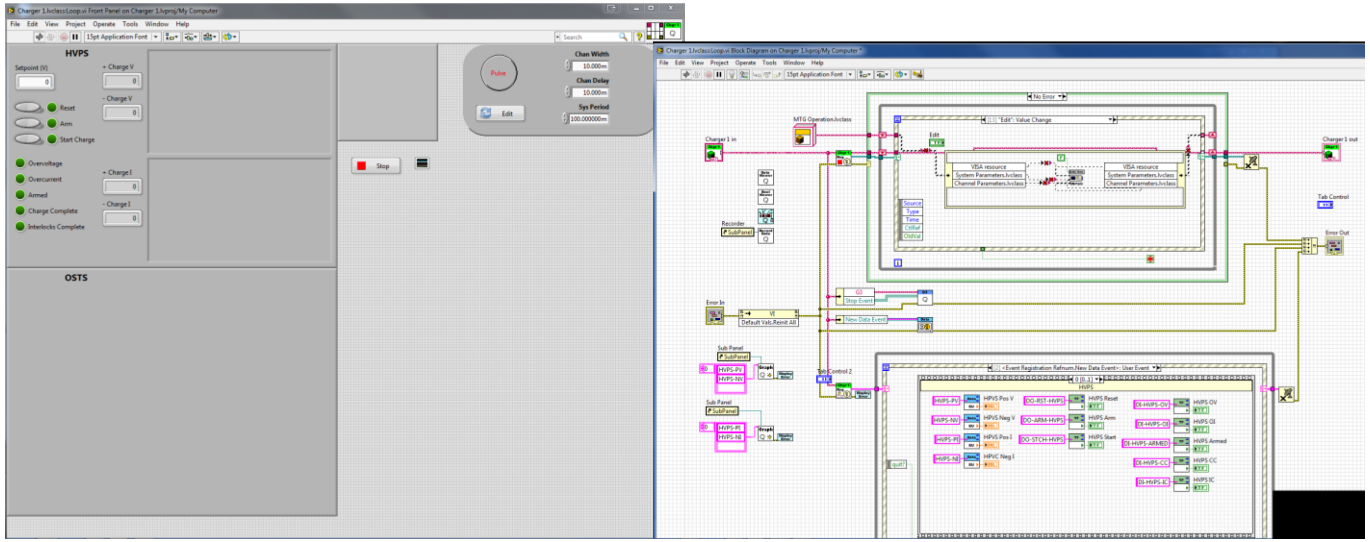
- A test facility for high power and thermonuclear fusion propulsion concepts, astrophysics modeling, radiation physics
- Located in the UAH Aerophysics Lab at Redstone
- The highest instantaneous pulsed power facility in academia – 572 kJ (1 TW at 100 ns)

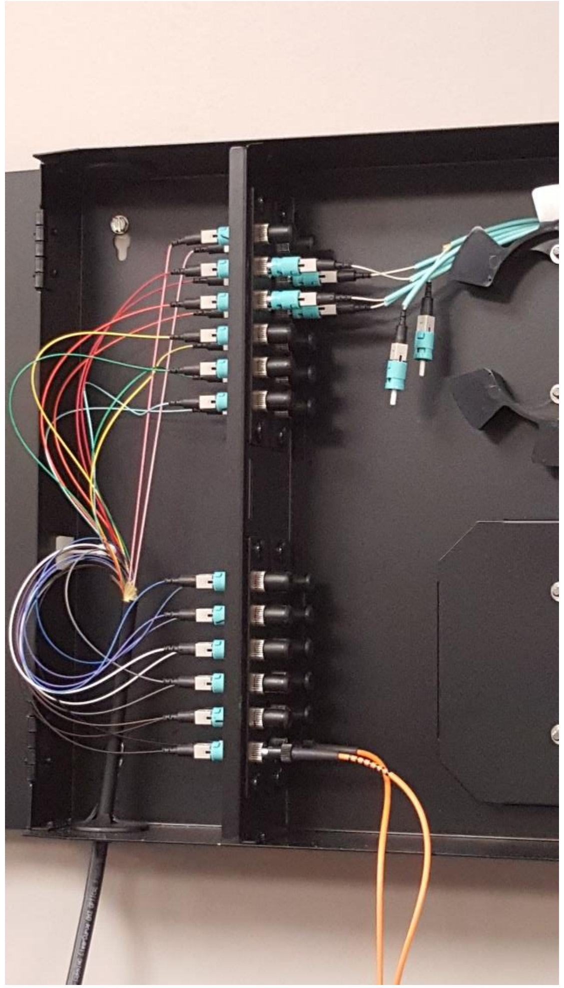
AEROPHYSICS RESEARCH CENTER UAH

Charger - 1

Project PI: Robert B. Adams, Ph.D.

- Progress on Control System
  - Hooking up 55 different GHz connections through fiber optics to monitor and control Charger – 1
  - LabView Control panels being programmed
    - Control Loop
    - Data Acquisition
  - Communication established from Test Control Center to Decade Module

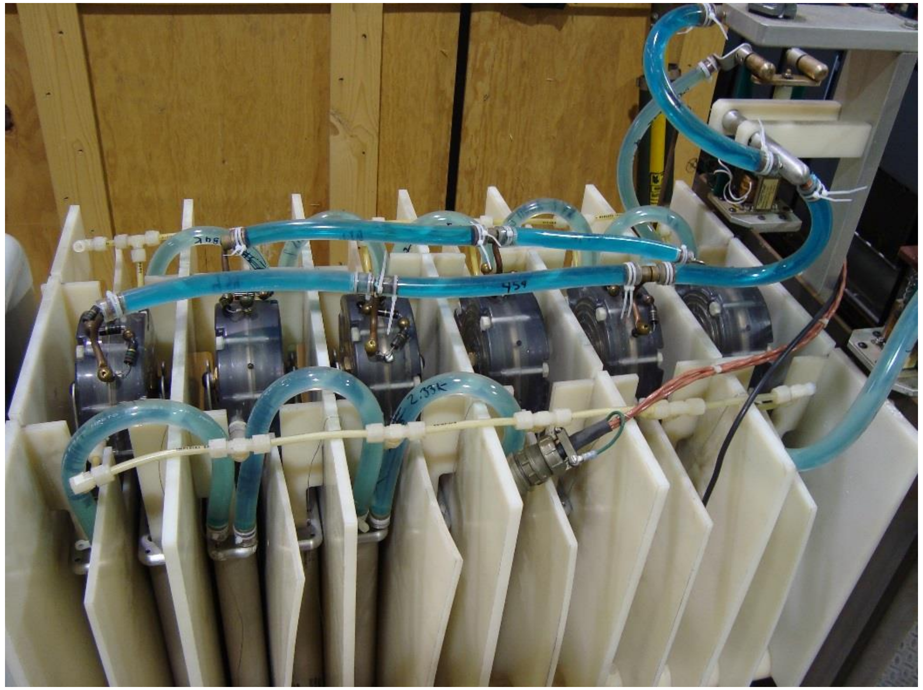




Trigging System

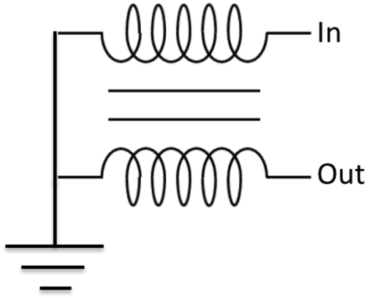
Project PI: Robert B. Adams, Ph.D.

- Trigger System Installation
  - Fiber optic signal triggers 501B transformer – procured, waiting for arrival
  - 501B triggers PT55 thyotron – being rebuilt in lab
  - PT55 triggering PA80 capacitor/switch – PT55 found/tested
  - PA80 creating 80kV bridge voltage for mini-Marx – under testing
  - Mini-Marx triggering Marx Bank – under refurbishment by UAH/NASA
- Refurb being assisted by recent location of original DECADE Quad hardware
  - Difficult to find some 20 yr old technology



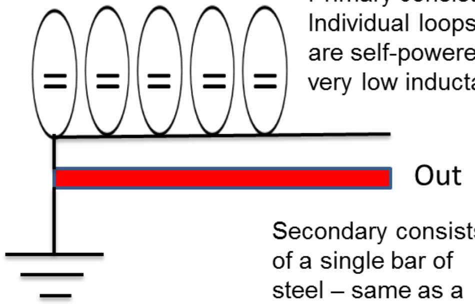
Linear Transformer Driver - Concept

Project PI: Robert B. Adams, Ph.D.



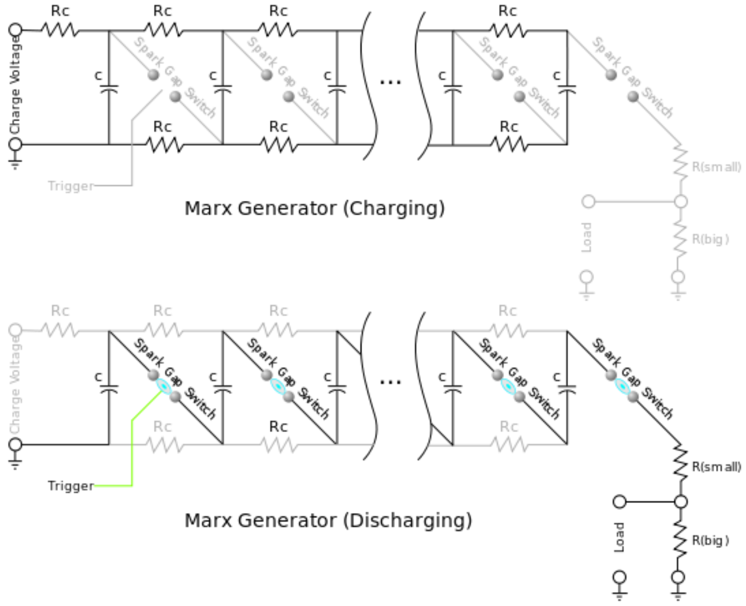
Primary consists of one wire looped many times around a single core – high inductance

Secondary consists of one wire looped many times around the same core

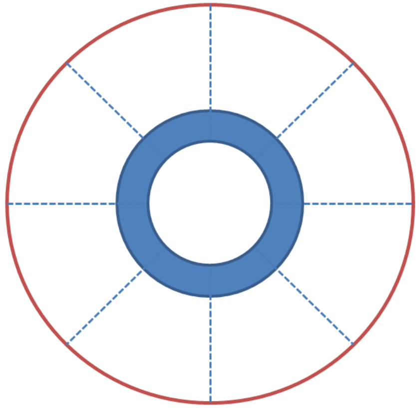


Primary consists of Individual loops that are self-powered and very low inductance

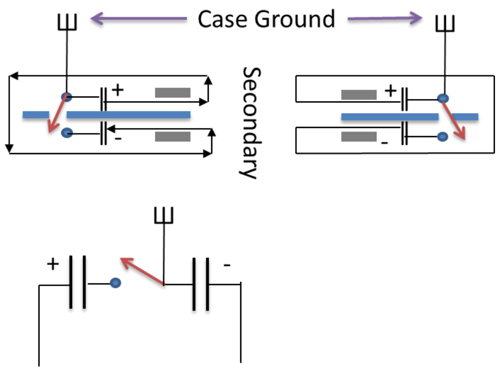
Secondary consists of a single bar of steel – same as a single wire loop.



Each 'Pie-Slice' provides a simultaneous parallel pulse to the inductor
For increased current (and thus B-Field)



Single Cavity



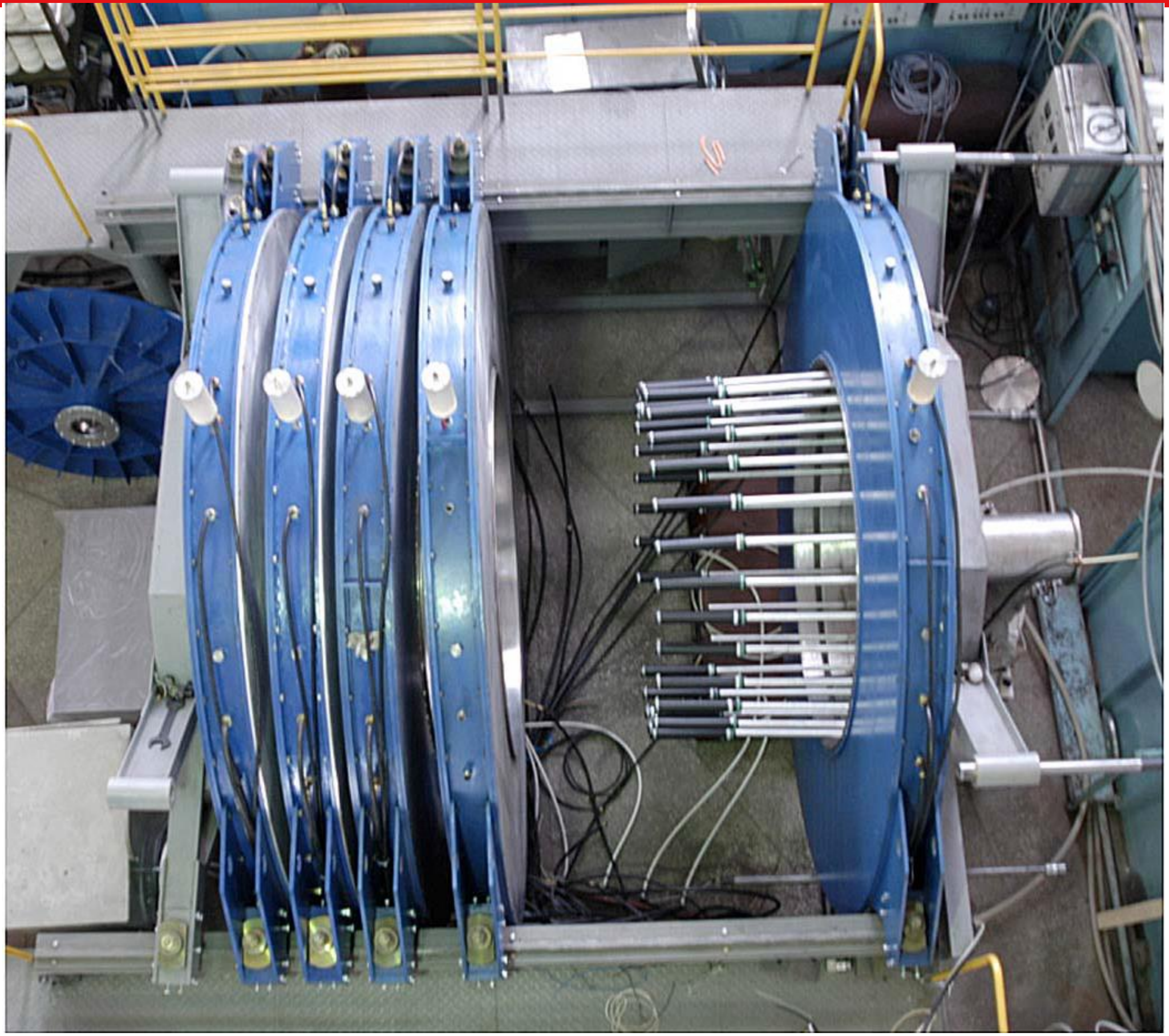
- Factor of 10 weight reduction in capacitor banks, structure, and associated power management.
- Enables faster pulsing giving higher
- thrust

Current LTD Technology

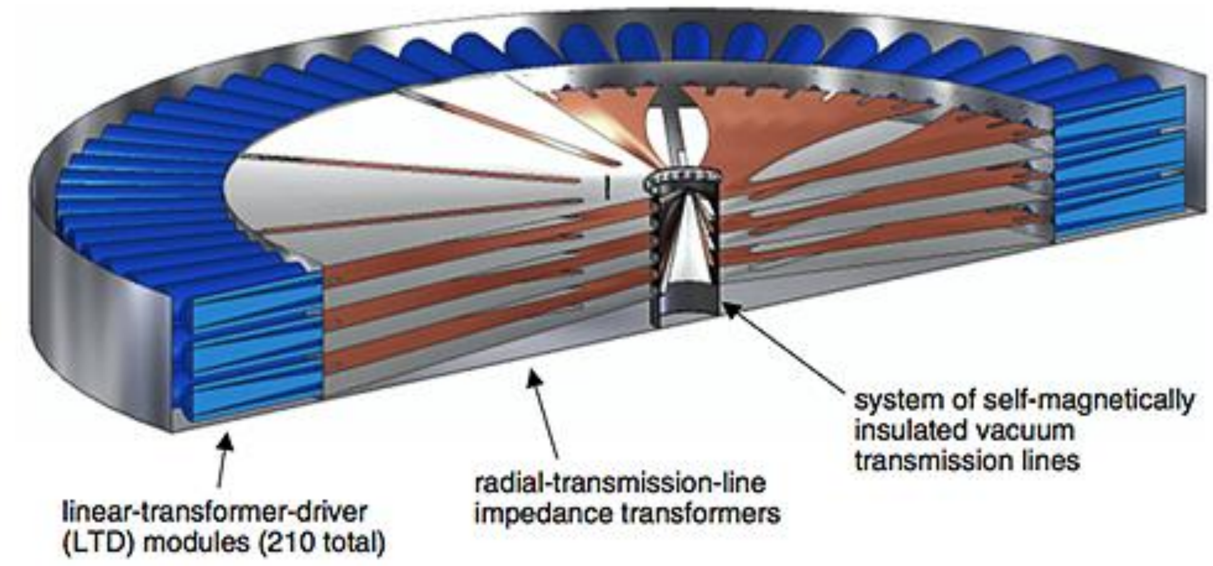
Project PI: Robert B. Adams, Ph.D.

- High Current Electronic Institute
- Single Cavity
  - 0.5 MA @ 100kV
  - 70-100 ns rise time
  - 0.1 Hz pulse rate
  - 2 m diameter
- 4 constructed
  - 3 at Sandia
  - 1 at Univ. Michigan

- LTD II – Sandia National Labs
  - Five Cavity Experiment
  - Reached 400 kV, 1 MA over 100 ns

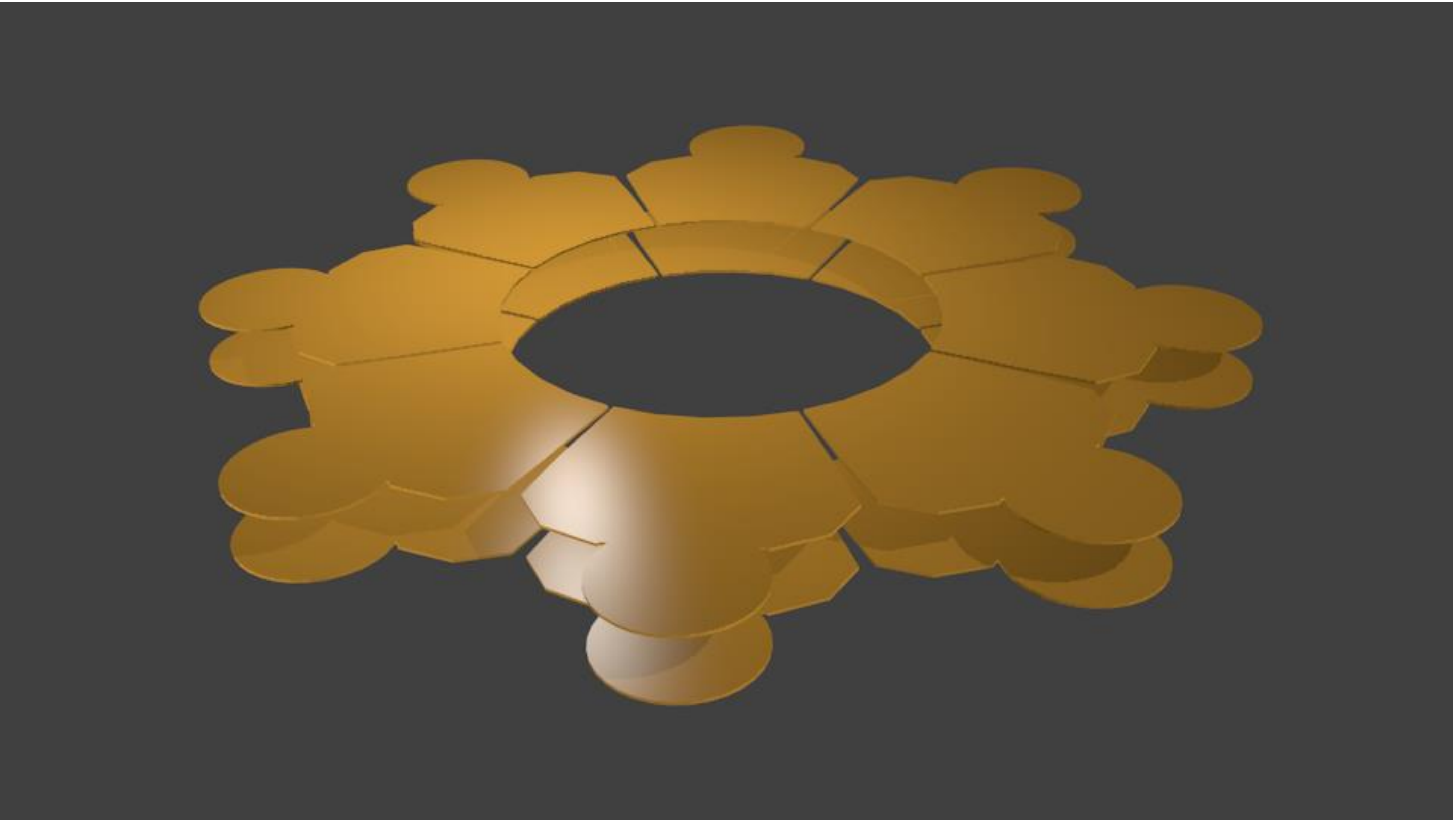


- Next Generation Z – Machine
  - The current Z-machine operates with Marx Bank technologies
  - Sandia has conceived two replacement options
    - Z-300 300 TW system that would fit in current Z-machine building
    - Z-800 800 TW system that, combined with Mag-LIF, is projected to reach engineering break even fusion



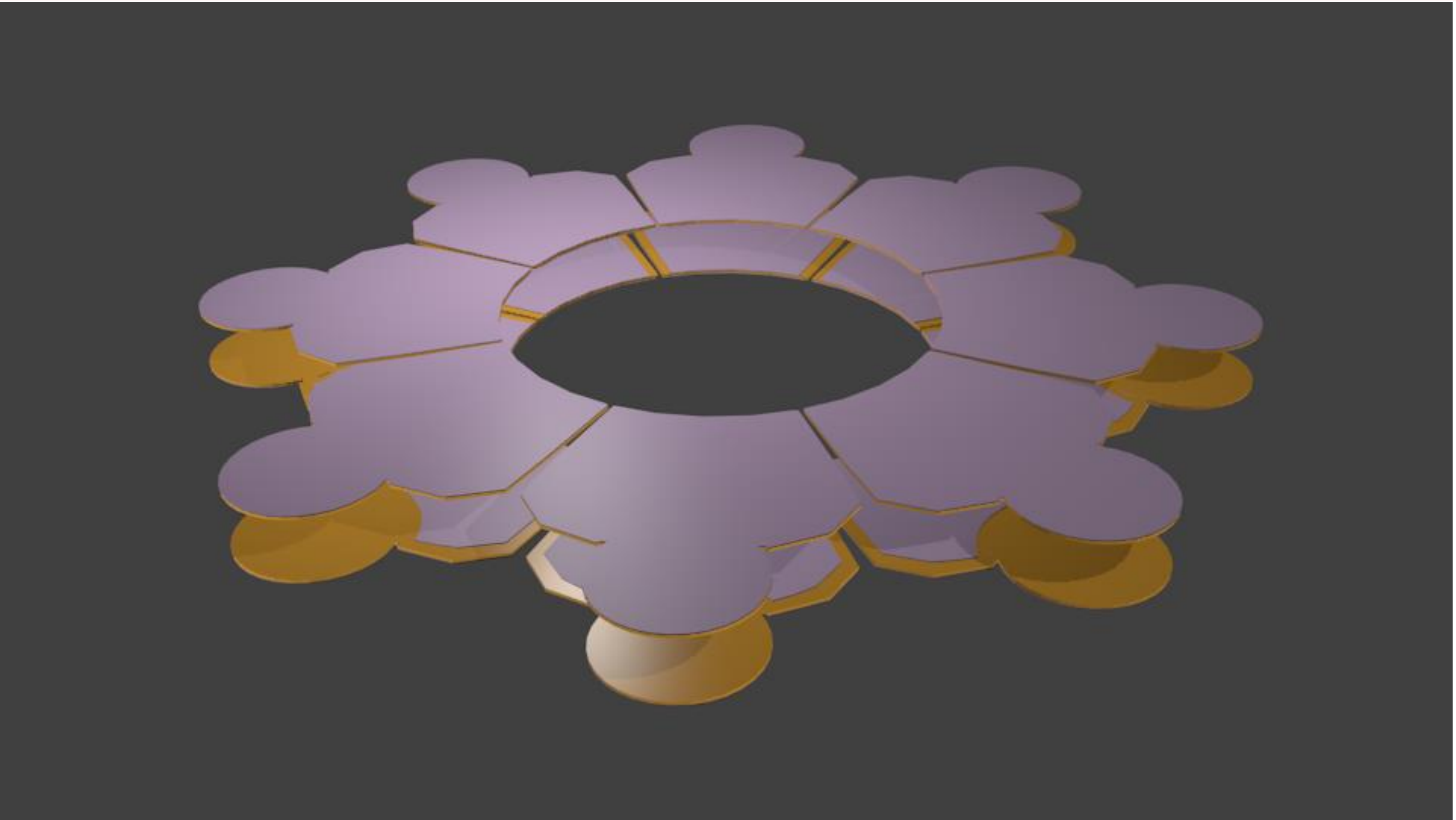
LTD Version 5

Project PI: Robert B. Adams, Ph.D.



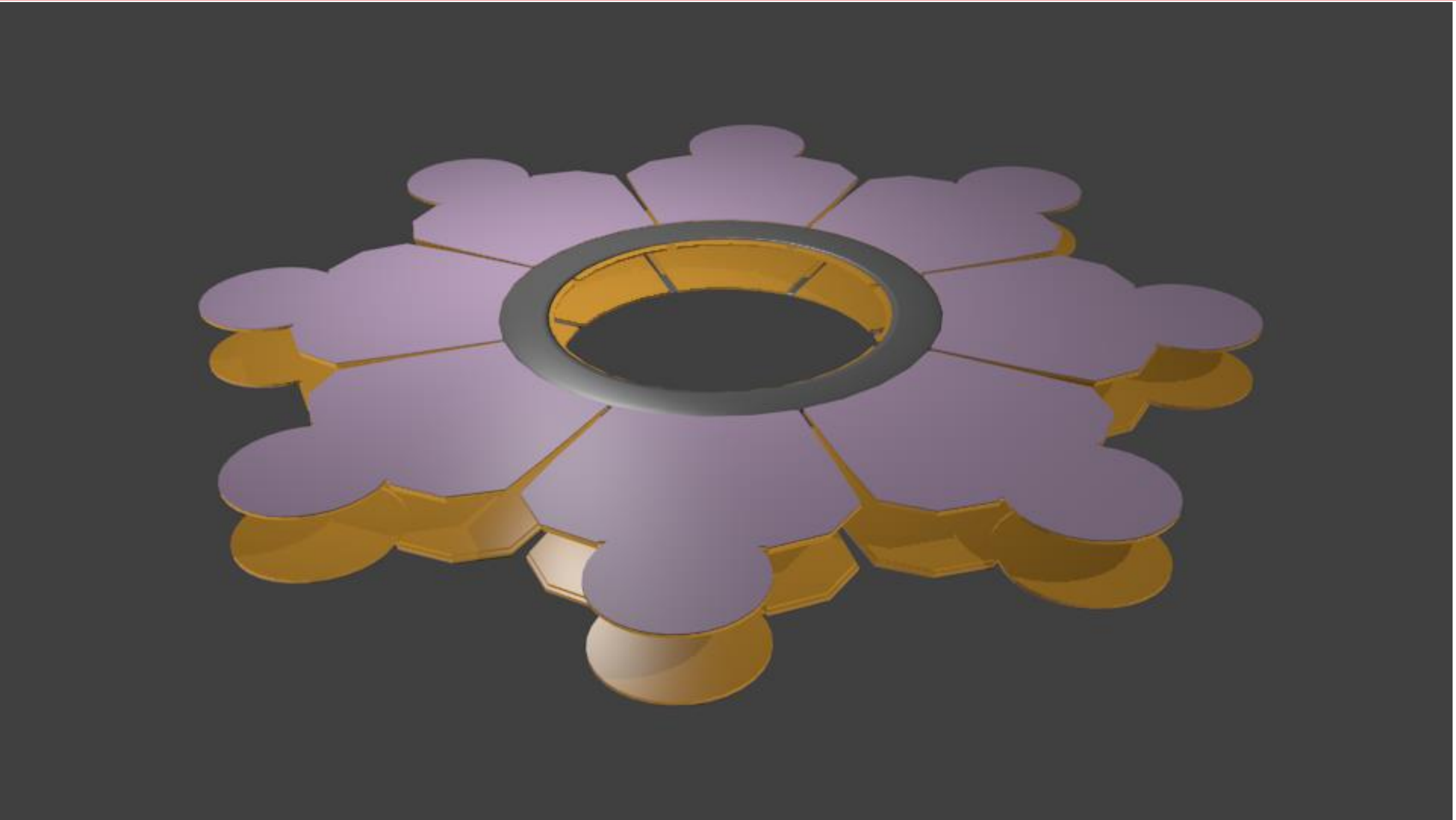
LTD Version 5

Project PI: Robert B. Adams, Ph.D.



LTD Version 5

Project PI: Robert B. Adams, Ph.D.



LTD Version 5

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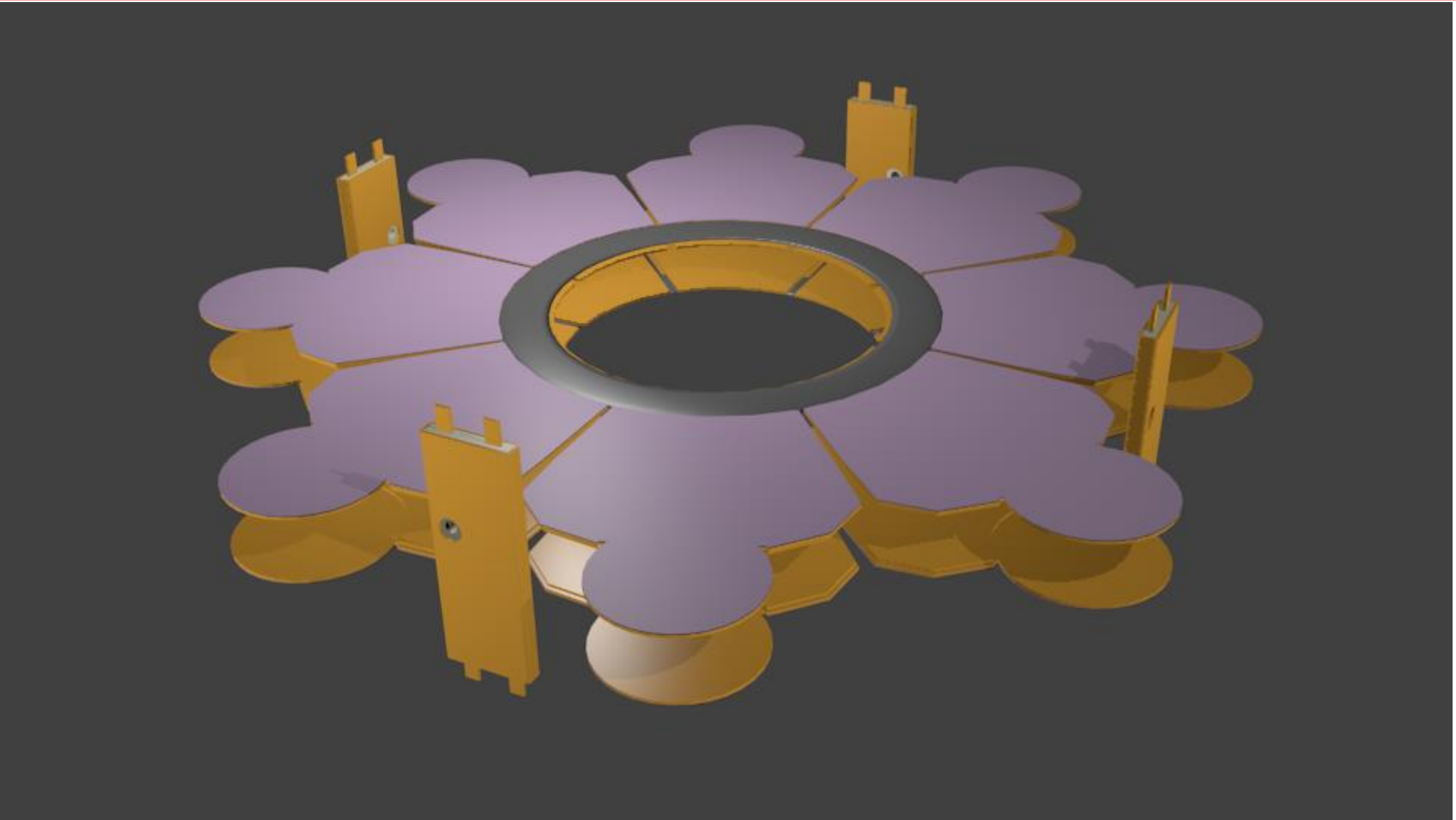
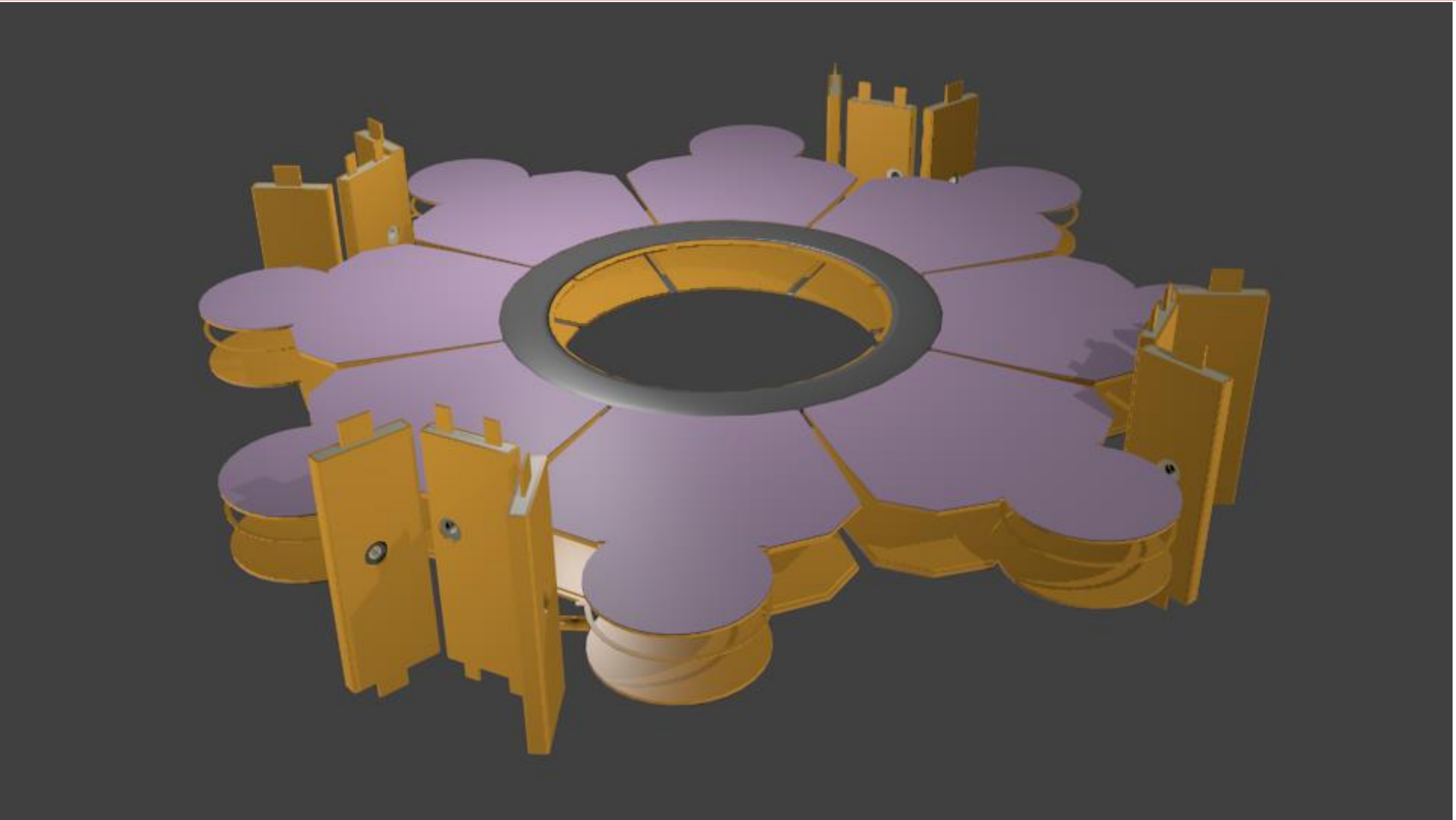


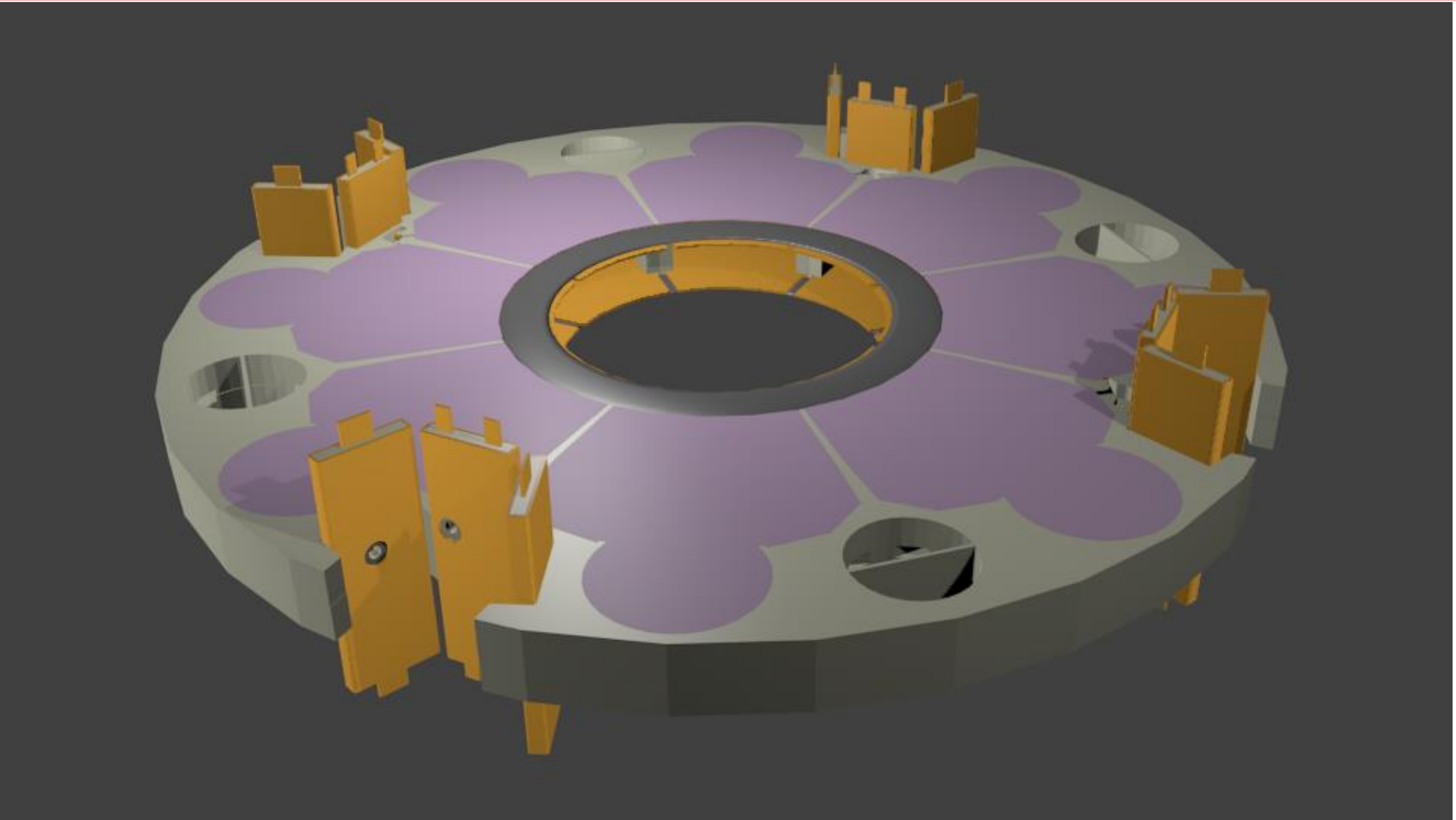
LTD Version 5

Project PI: Robert B. Adams, Ph.D.



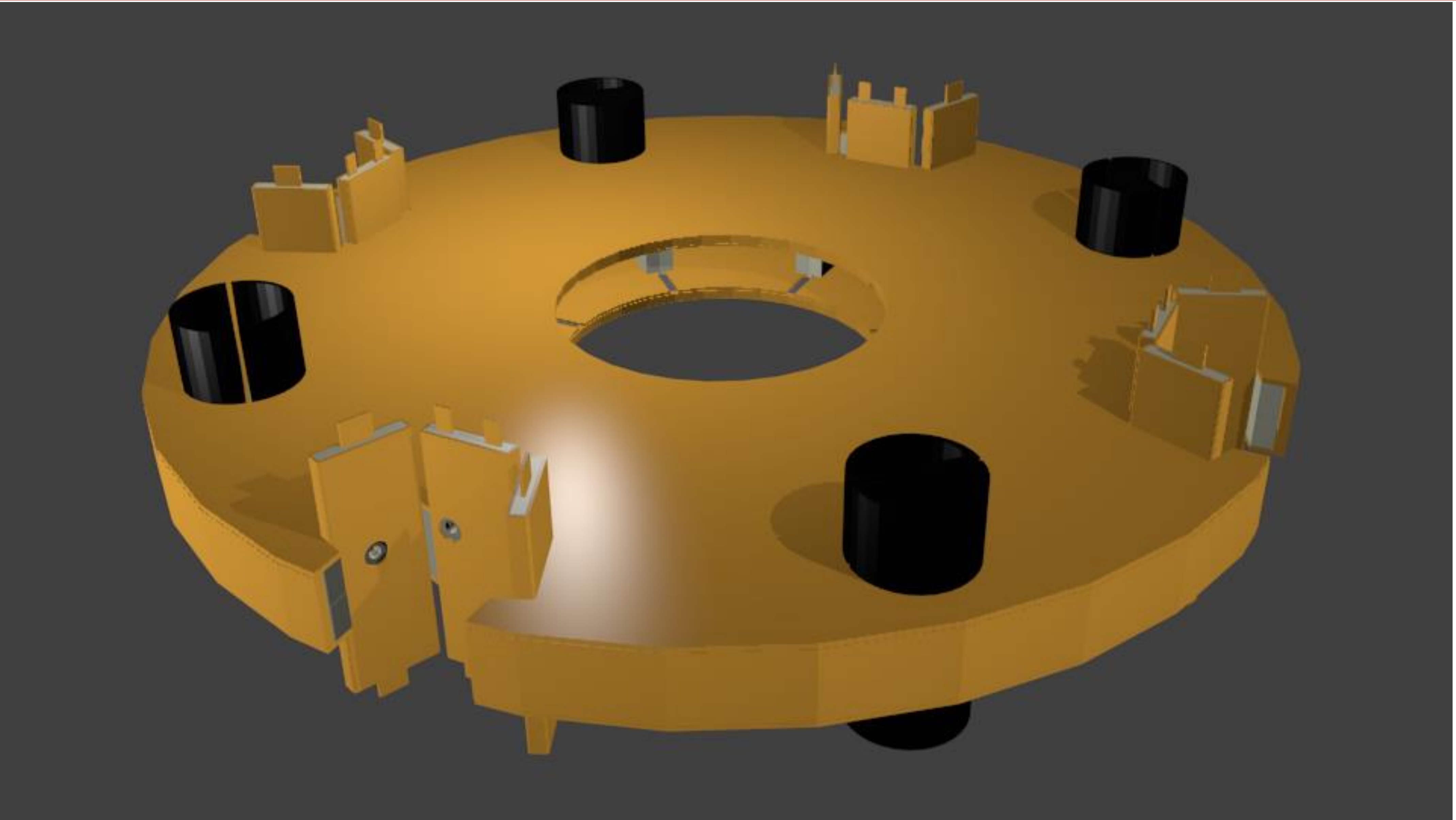
LTD Version 5

Project PI: Robert B. Adams, Ph.D.



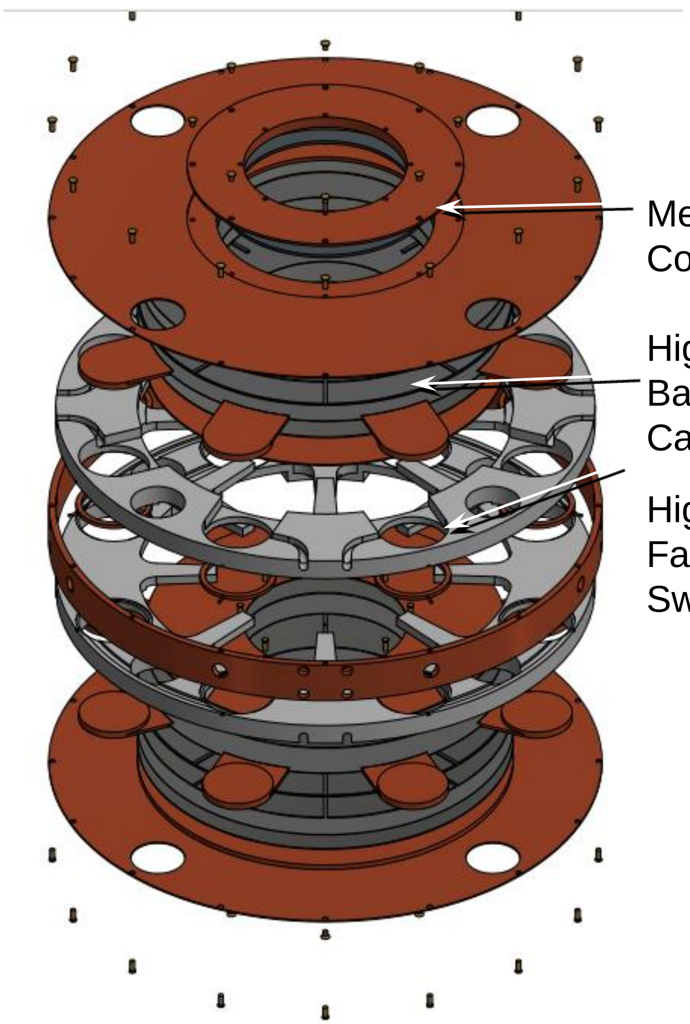
LTD Version 5

Project PI: Robert B. Adams, Ph.D.



LTD Version 6

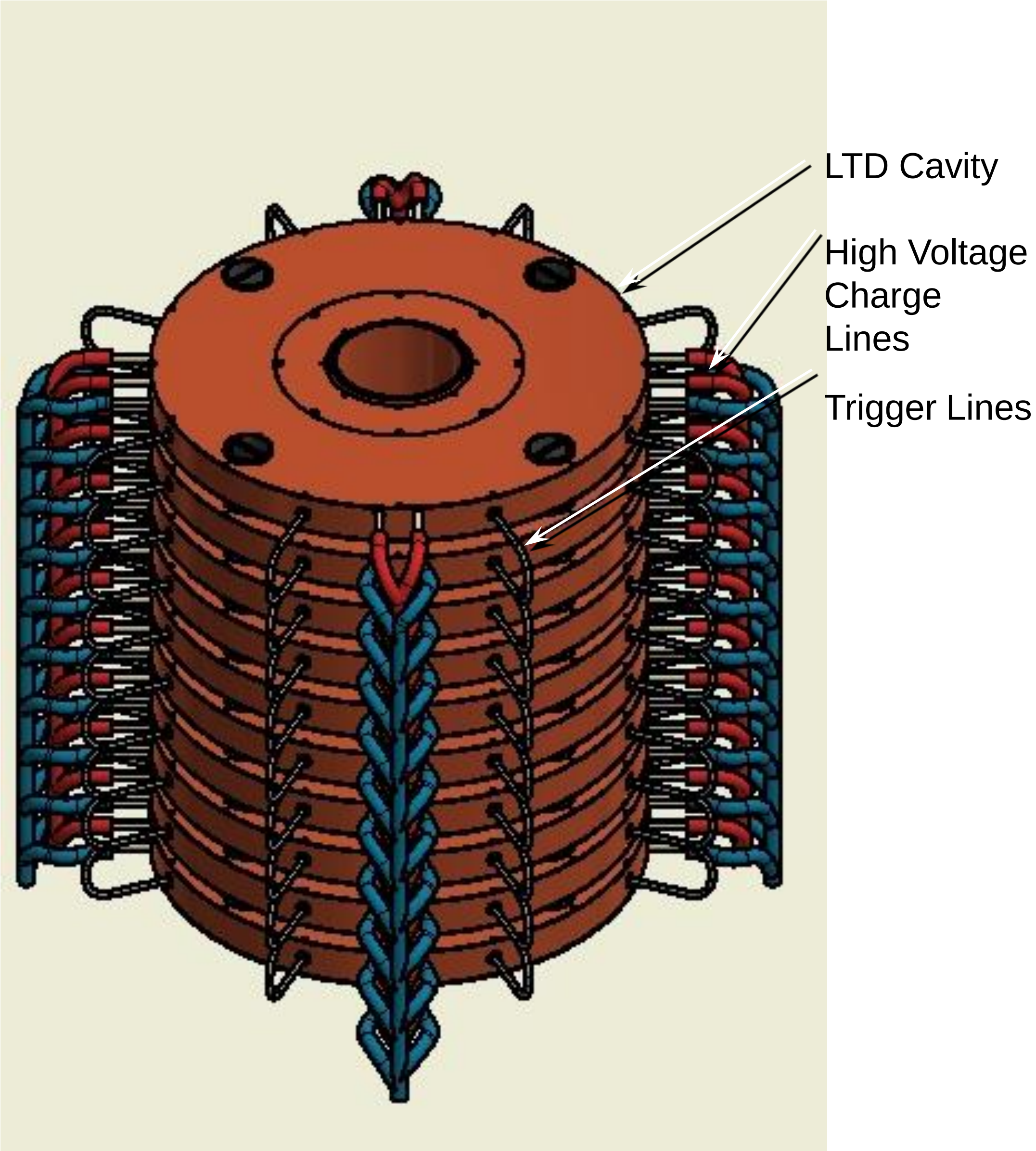
Project PI: Robert B. Adams, Ph.D.



LTD Stack

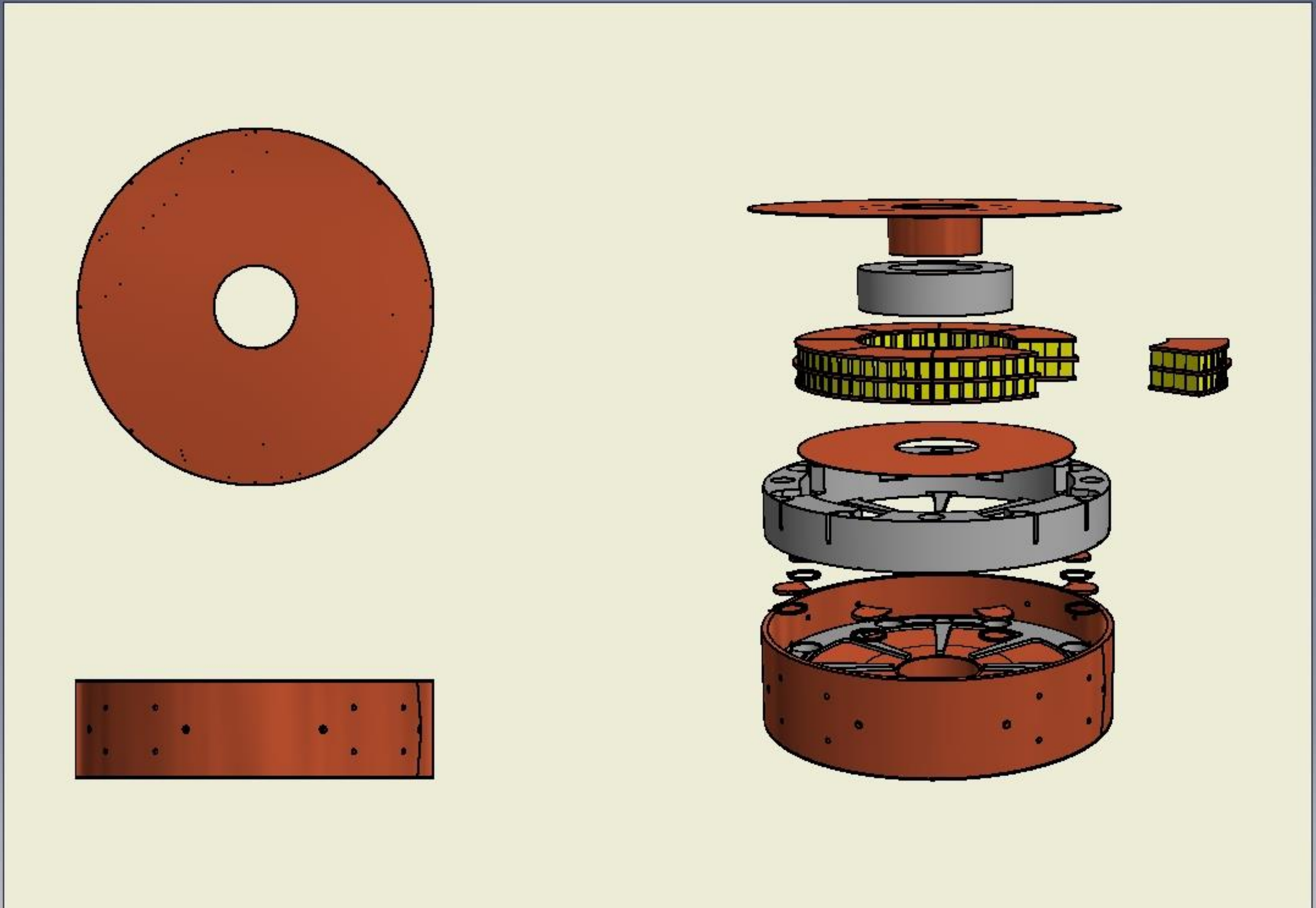
Project PI: Robert B. Adams, Ph.D.

- Develop Linear Transform Driver (LTD) Stack that can be used in pulsed plasma and fusion propulsion systems



LTD Version 7

Project PI: Robert B. Adams, Ph.D.



Research and Development Support for PuFF ,Charger – 1, LTDs

Project PI: Robert B. Adams, Ph.D.

Historical timeline for basic R&D activities related to PUFF

- Charger-1, PuFF and LTD development provides a unique high power research and development capability for MSFC
- Limited funding from varied sources and partners – focused on small hardware evaluations
- Striving to maintain forward momentum

April 2012
UAH receives DM2 from DTRA

June 2012
CSDWG awards 130K to effort

September 2012
MSFC Chief Technologist awards 0.58 FTE, 57k

December 2012
UAH receives 300k from AL Innov. Fund

February 2013
Initial mating of Charger-1 components

July 2013
NIAC Phase 1 granted for PuFF concept

May 2014
First implosion of Li wire

October 2014
CIF awarded – LTD Development

April 2015
First firing of LTD cavity

July 2015
Boeing, UAH, MSFC CSDWG commits 300k, 0.8 FTE to Charger-1

October 2015
CIF continuation– LTD Development

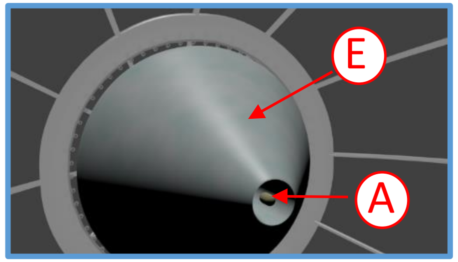
Jan 2016
CSDWG commits 0.6 FTE

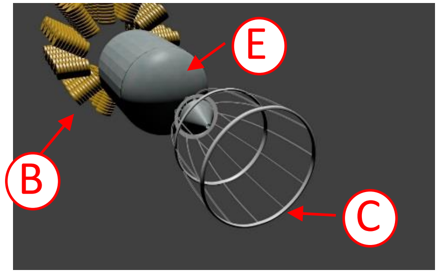
March 2016
ZP Advanced Propulsion FTEs

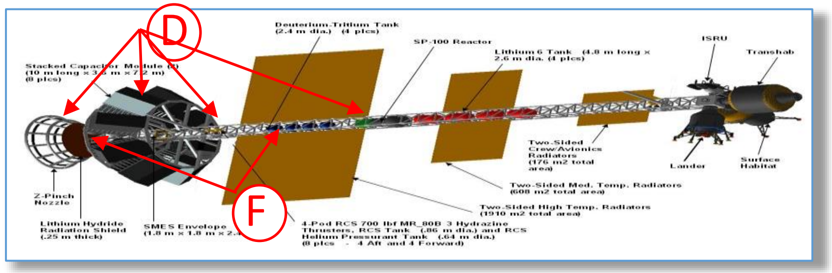
October 2016
CIF– Nuclear target/Mat'l mgmt.

Key Technologies – Progression from Physics to Engineering

Project PI: Robert B. Adams, Ph.D.







Maturation

Physics / R&D

A - Target	B - Linear Transformer Drivers (LTD)	C - Magnetic Nozzle (MN)	D – Recharge System	E – Lithium Injectors	F - Target Storage / Dispenser
Implosion Capsule	**Pulsed power storage, discharge and compression system**	**Directs fission/fusion products and recovers energy for next pulse**	**Pulse generation and onboard power storage/generation**	**Lithium tankage / distribution systems to provide target liner and power conduction path**	**Maintains targets in non-critical configuration, injects into nozzle**
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	

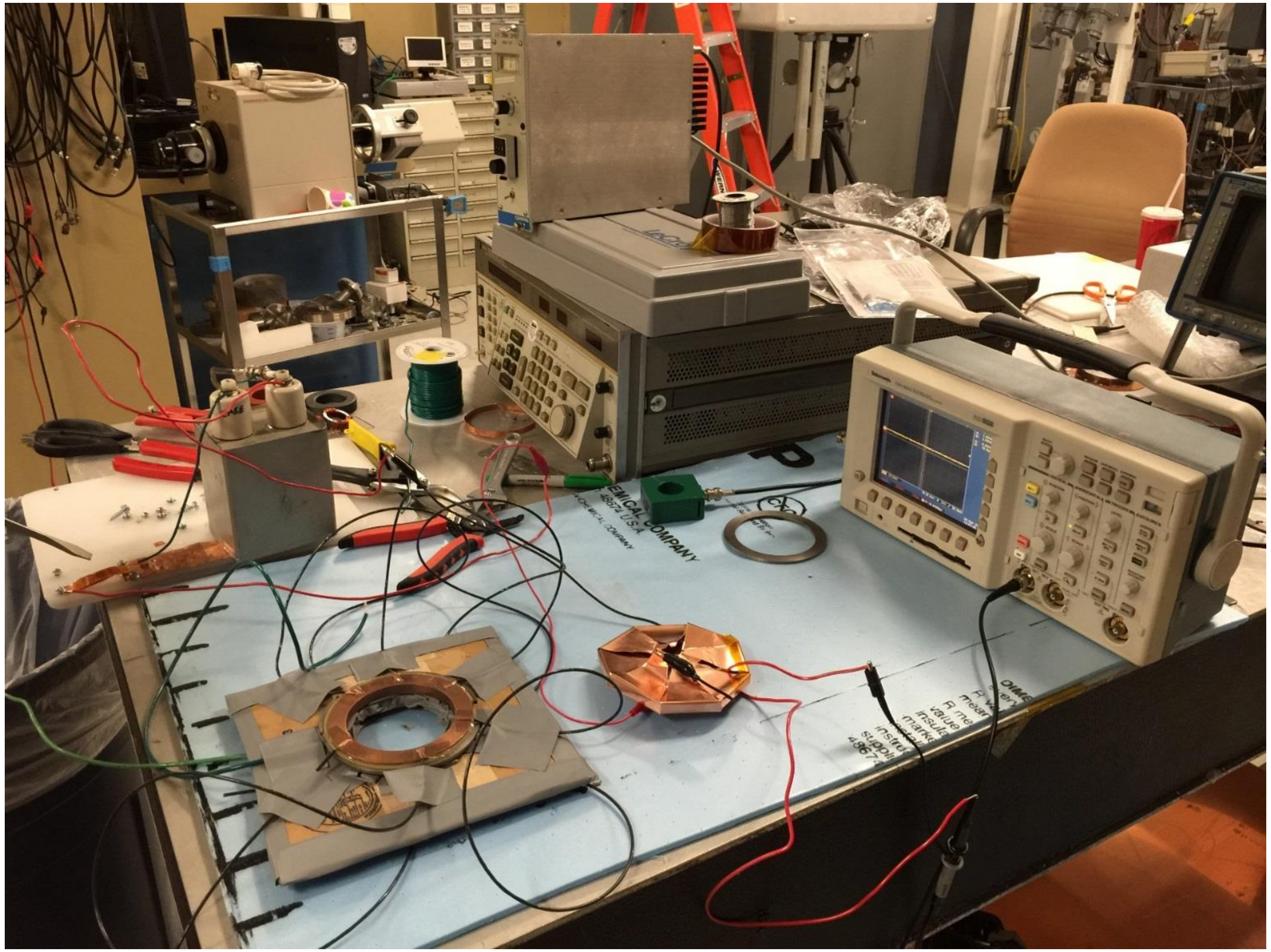
Engineering

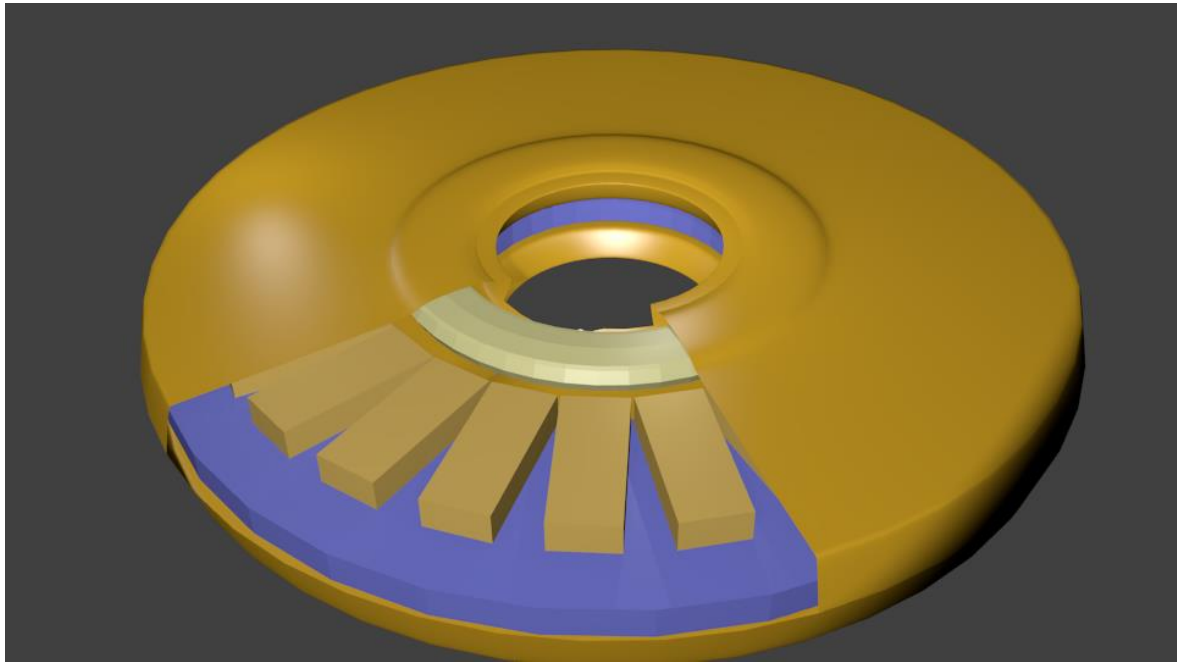
Backup Charts

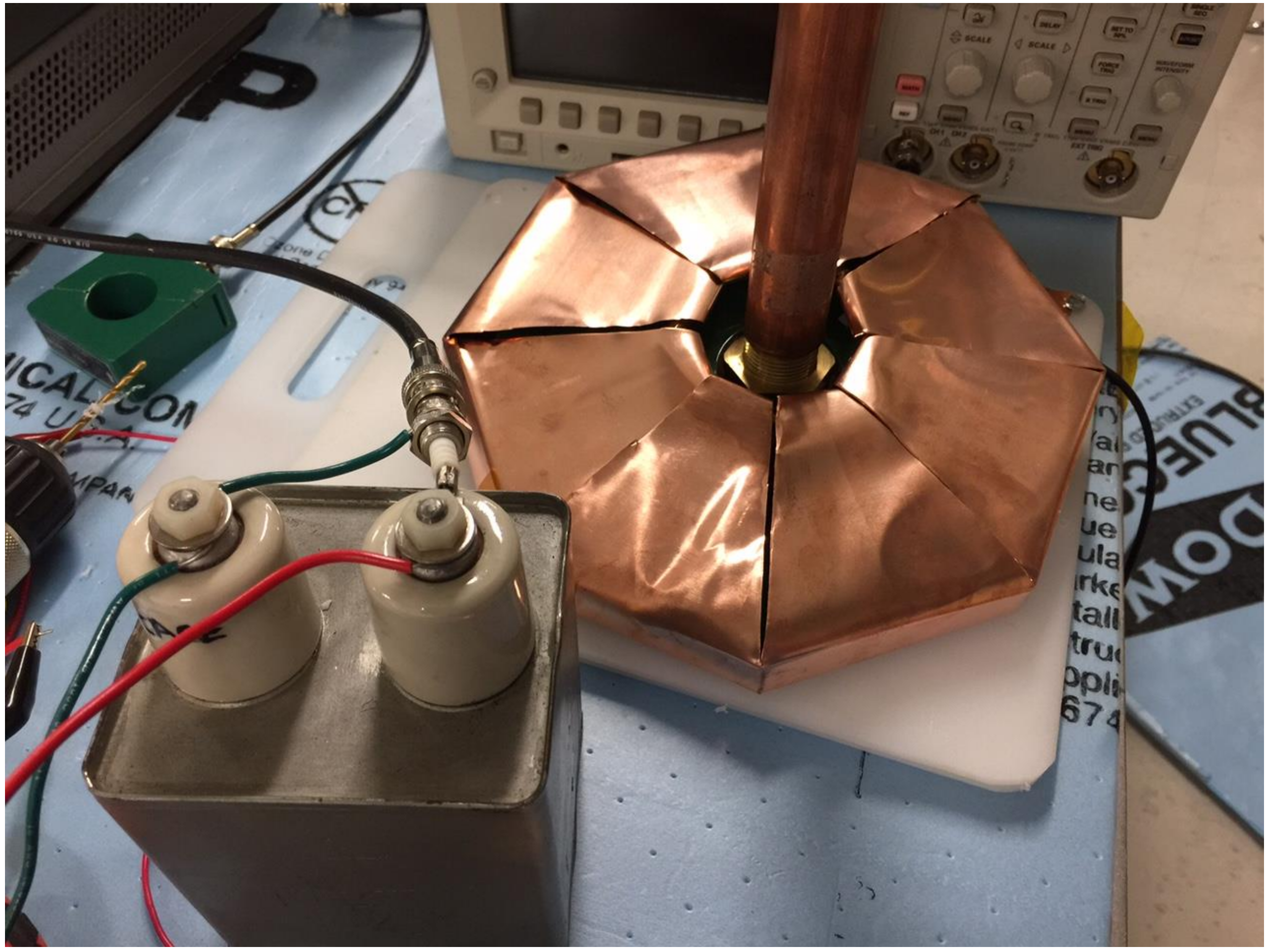
Project PI: Robert B. Adams, Ph.D.

LTD versions 1 and 2

Project PI: Robert B. Adams, Ph.D.



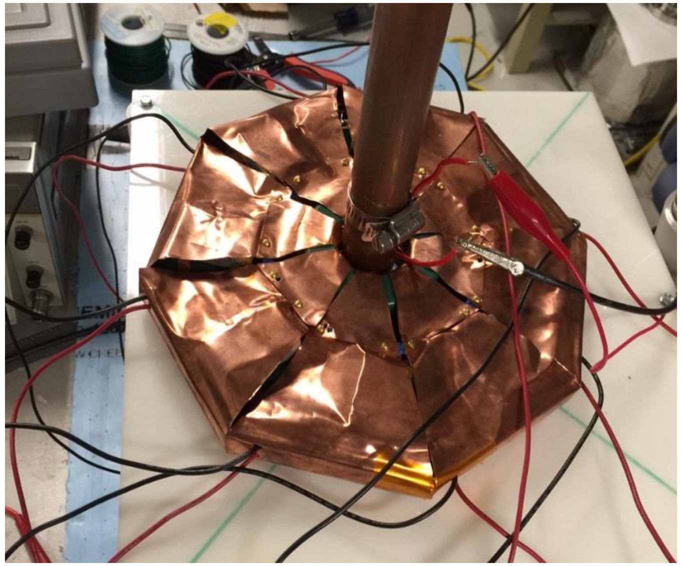


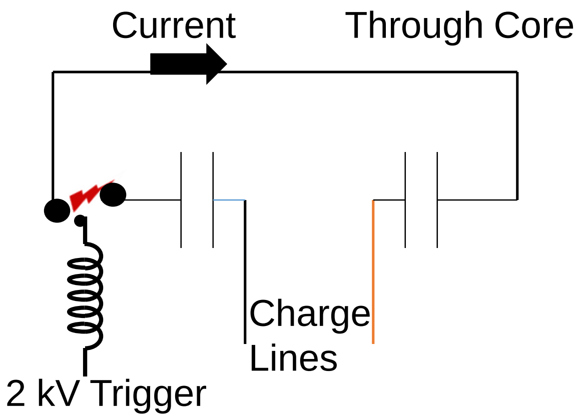


- Larger shell
- Testing at +/- 1 kV
- Still using 1 brick
- Measuring induced current in central shaft

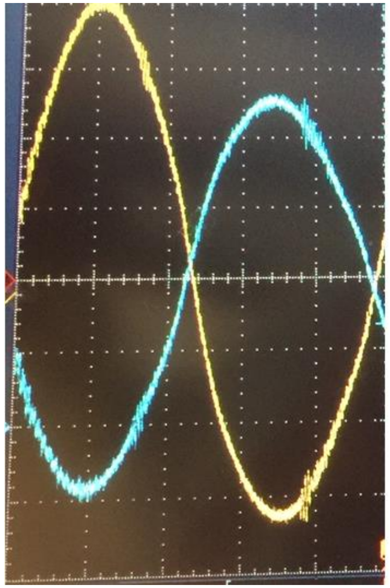
LTD version 4

Project PI: Robert B. Adams, Ph.D.





Each of 8 Bricks



- Tested V6 Cavity with individual triggers for each brick.
- Each of these triggers was isolated with a 500uH inductor.
- Resulting pulse had 50% shorter rise time due to much shorter (and hence lower inductance) circuit path.