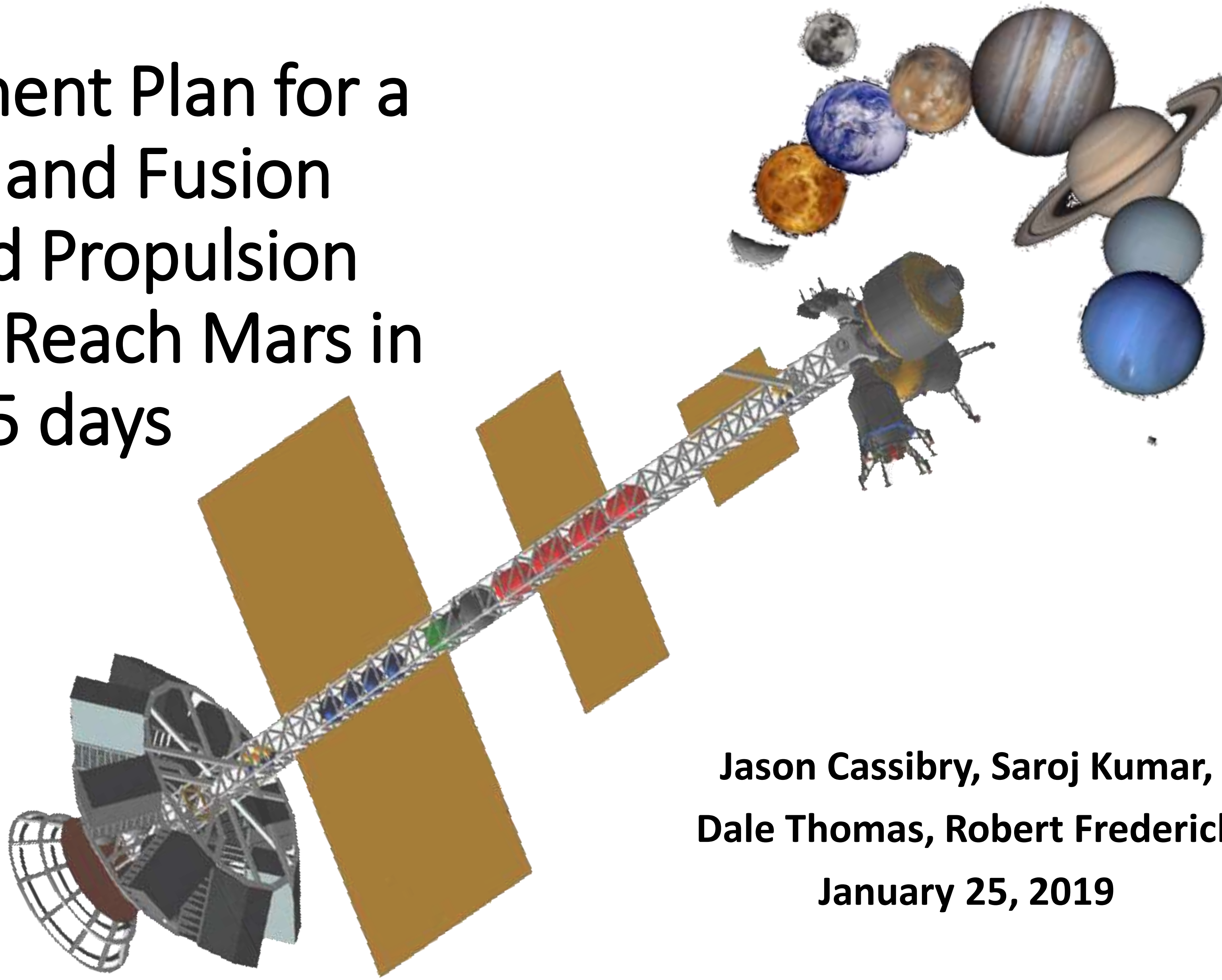
Development Plan for a Fission and Fusion Powered Propulsion System to Reach Mars in 45 days



Jason Cassibry, Saroj Kumar,

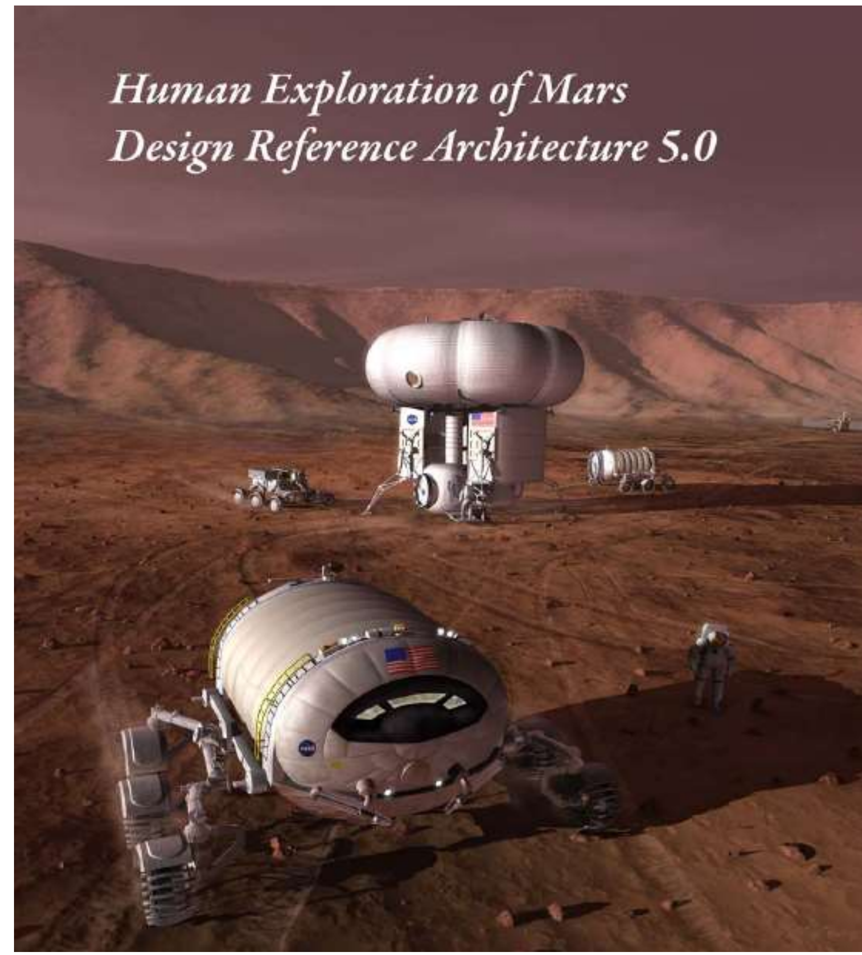
Dale Thomas, Robert Frederick

January 25, 2019

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

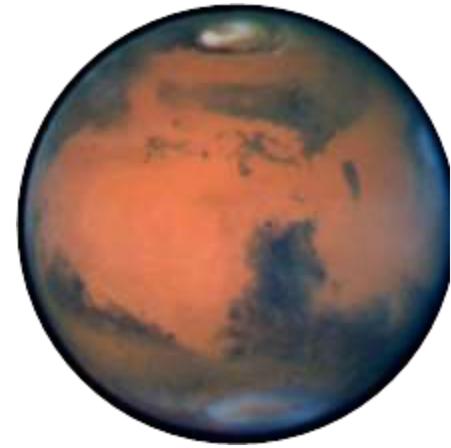
Why Send Humans to Explore Other Planets?

- Faster speed and higher efficiency to optimize field work
  - Agility and dexterity to go places that are difficult for robotic access
  - Innate intelligence, ingenuity, and adaptability to evaluate in real time and improvise to overcome surprises
- Overcome communication problems
  - time lag with mission control, e.g. 6- to 20-minute communications transit time for Mars
  - small number of daily uplink and downlink communications passes

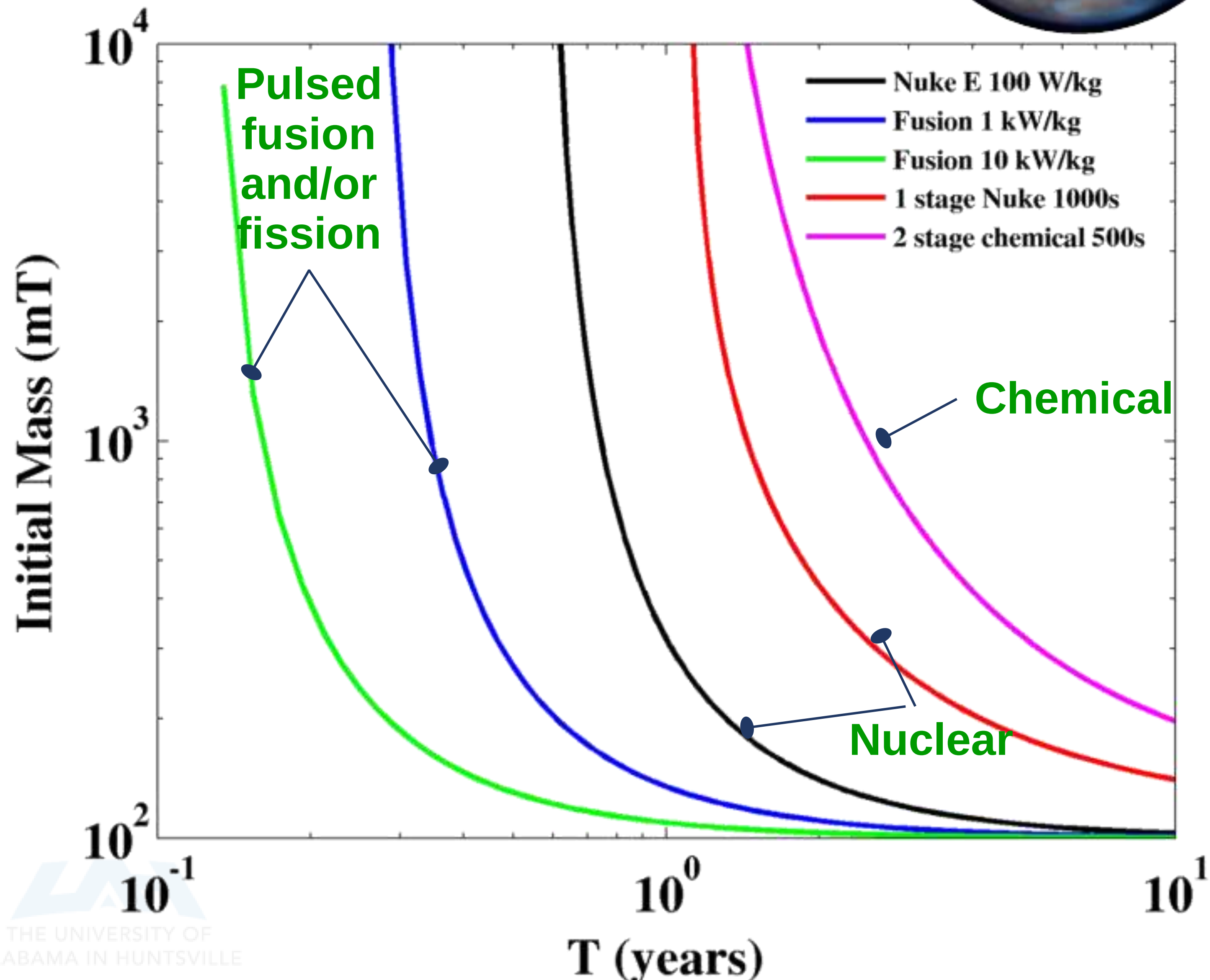


Benefits of Nuclear Technology in Space

Routine Human Piloted Mars Missions



Roundtrip to Mars Initial Mass in LEO for 100 mT payload



Performance

- Larger Payloads
- KW to MW of 'House' Power

Safety

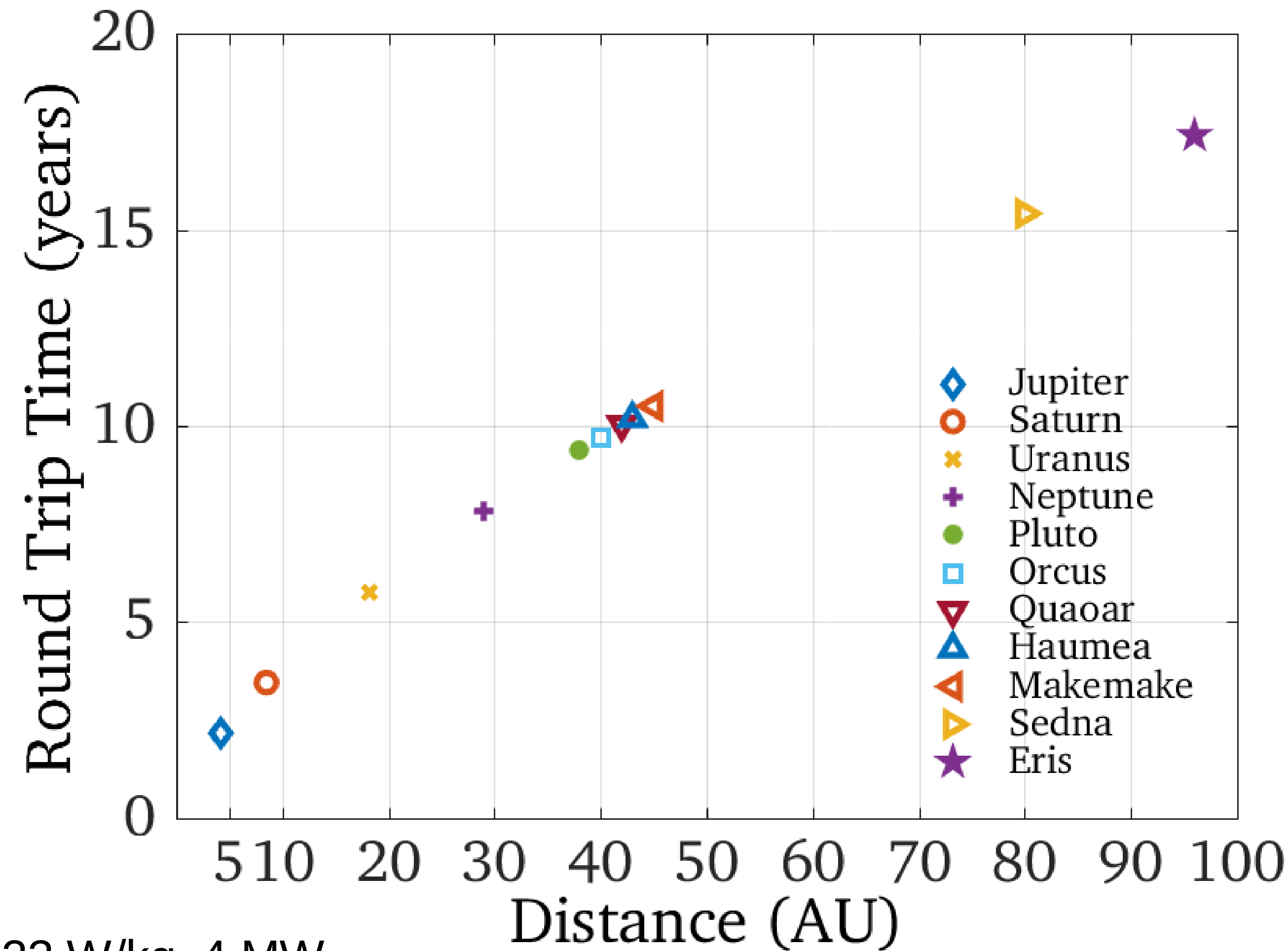
- Faster Trip Times
- Mission Abort Capability

Benefits of Nuclear Technology in Space

Rapid Sample Return Missions from Deep Space

Roundtrip sample return trip times for a 100 metric ton (IMLEO) vehicle

- α=1 kW/kg
- Assumed distance is the perihelion of the celestial body orbit

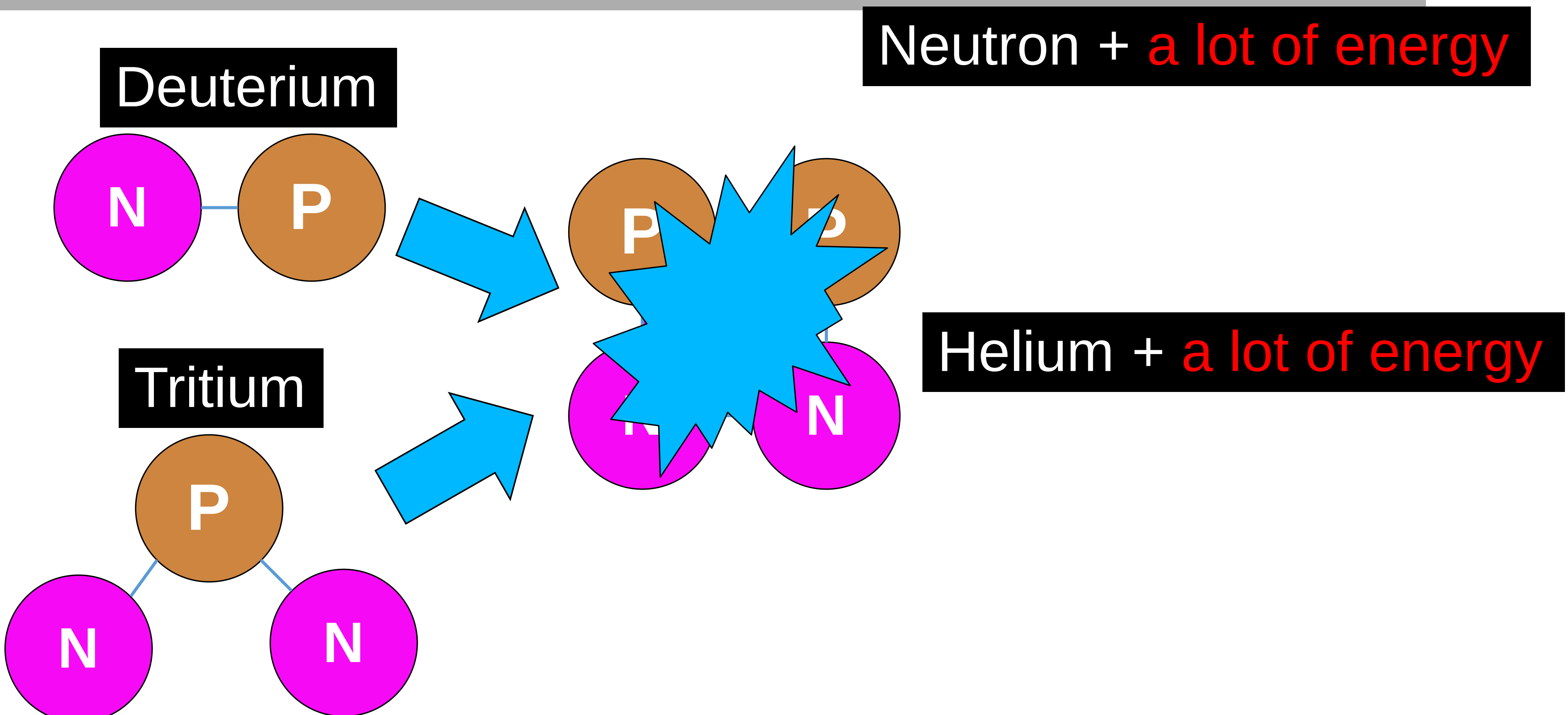


Comparable specific powers

- Diesel engine on freight train 23 W/kg, 4 MW
- NERVA thermal nuclear rocket 41 kW/kg, 1.4 GW
- KRUSTY nuclear electric reactor, 6 W/kg, 6 kW

What is fusion?

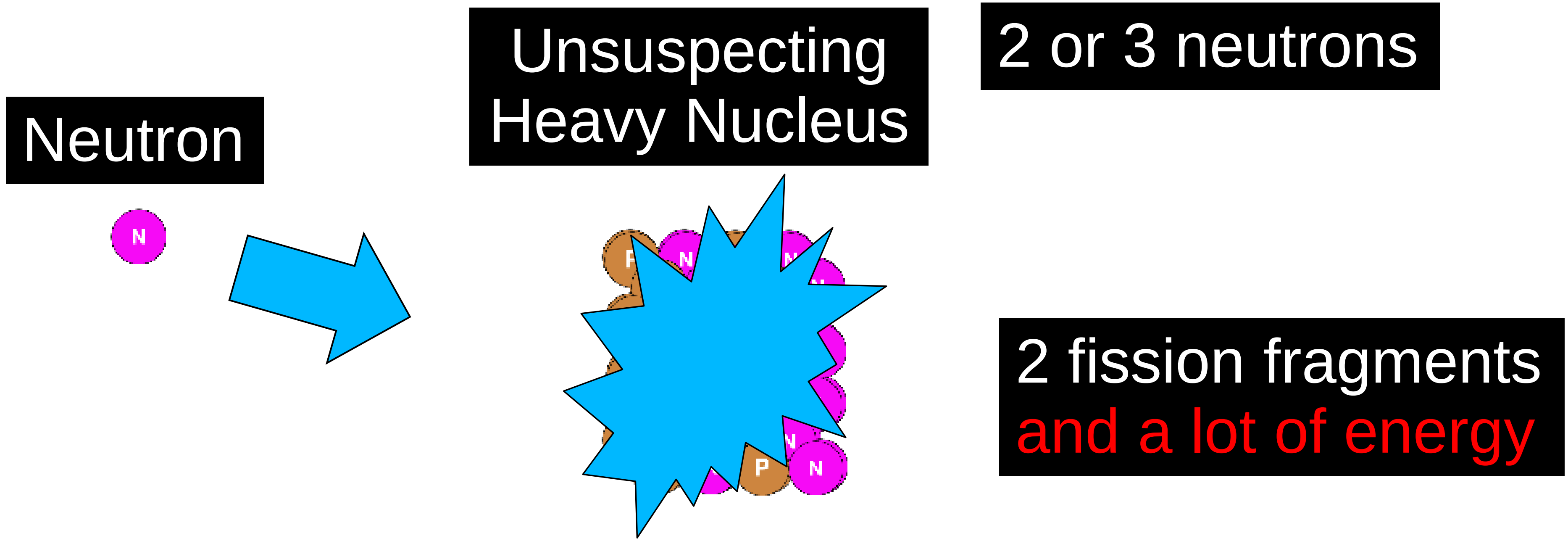
- The process by which multiple like-charged atomic nuclei join together to form a heavier nucleus.



THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

What is fission?

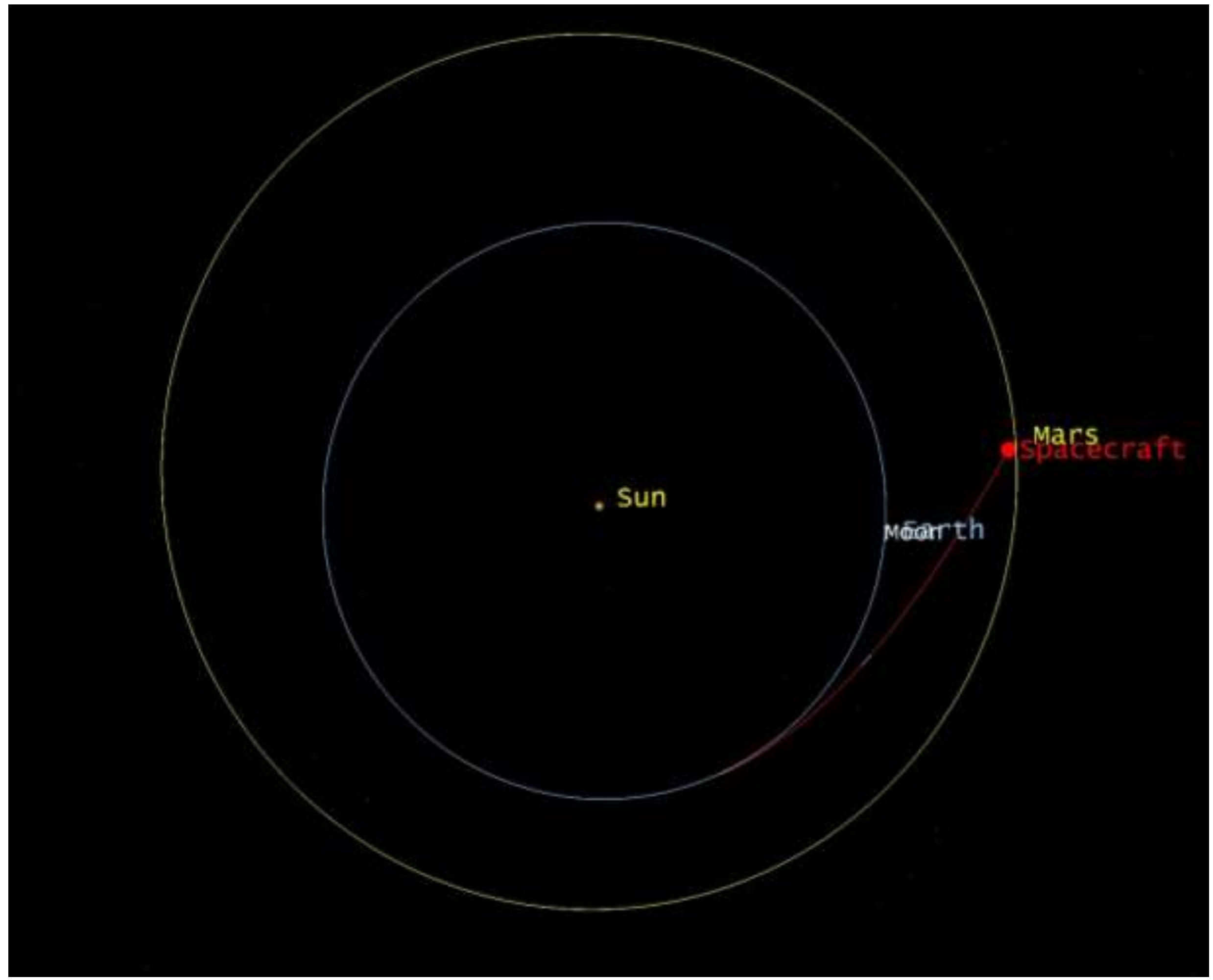
- The process by which a neutron strikes a heavy nucleus, causing the nucleus to split into two smaller fragments.



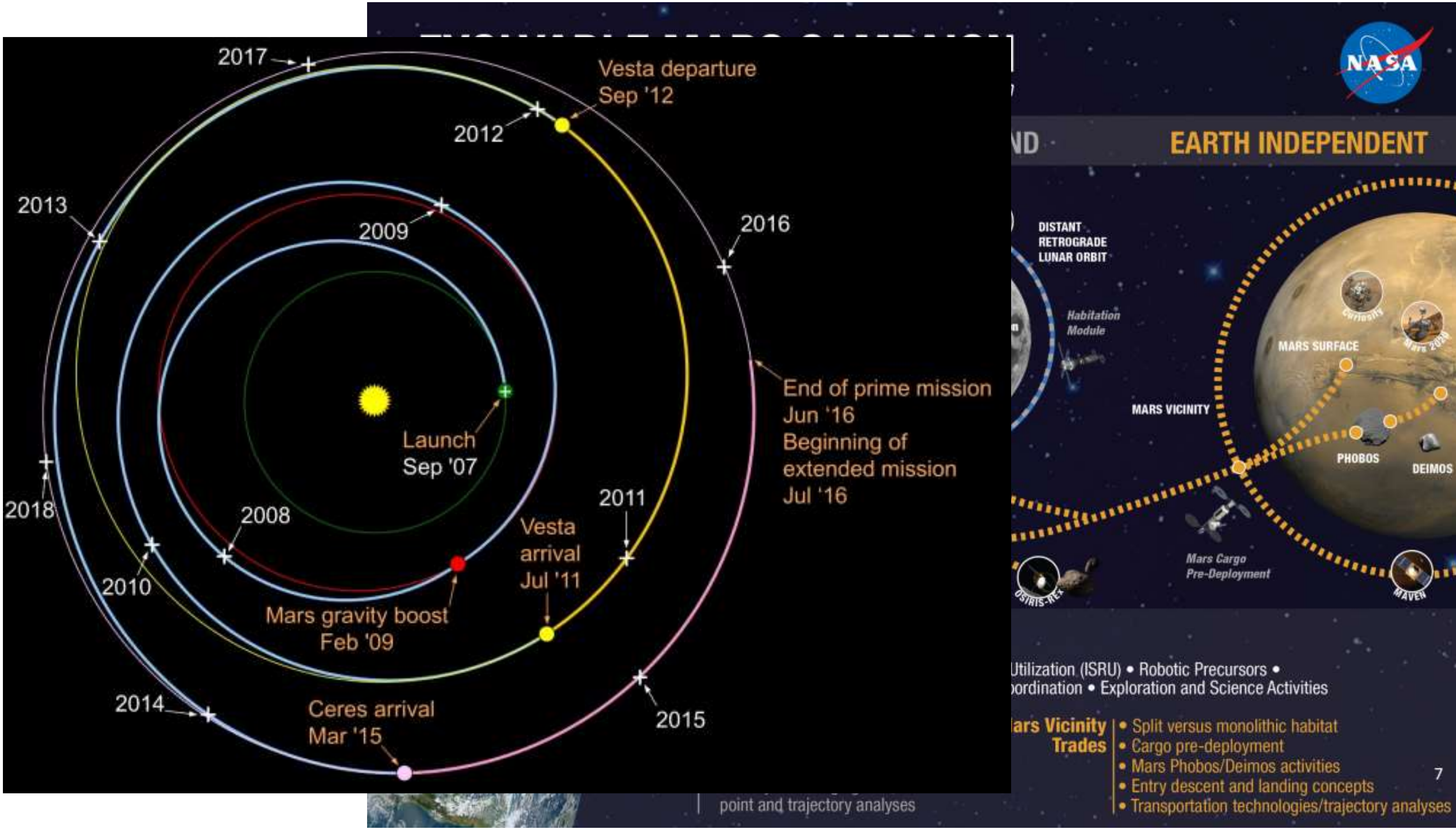
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Preliminary medium fidelity analysis based on Mars mission with thrust of 250N and Isp of 5000 sec. The analysis was performed for heliocentric phase trajectory i.e, spacecraft departure from the Earth's SOI to Mars (flyby). The total trip time is 62 days with 2 days of coast phase.

Key challenges
- Departure from Earth sphere of influence
- Capture at Mars orbit
- The minor challenge that controlled thermonuclear fusion has not been accomplished in its 60 year history …



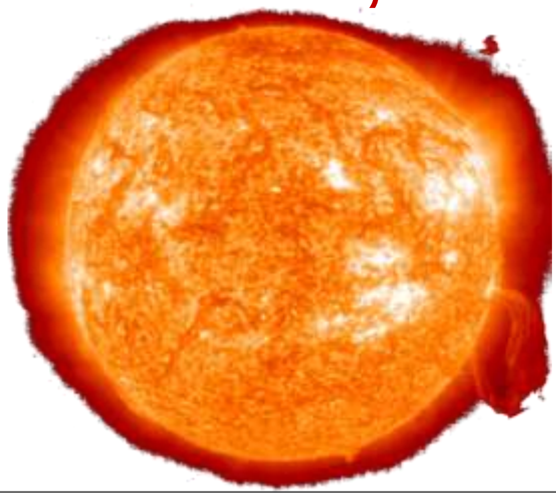
The Problem for Advanced Propulsion Departure



THE UNIVERSITY OF
ALABAMA IN HUNTSVILLE

The Problems for Fusion

Temperature > 100,000,000 ^{o}K

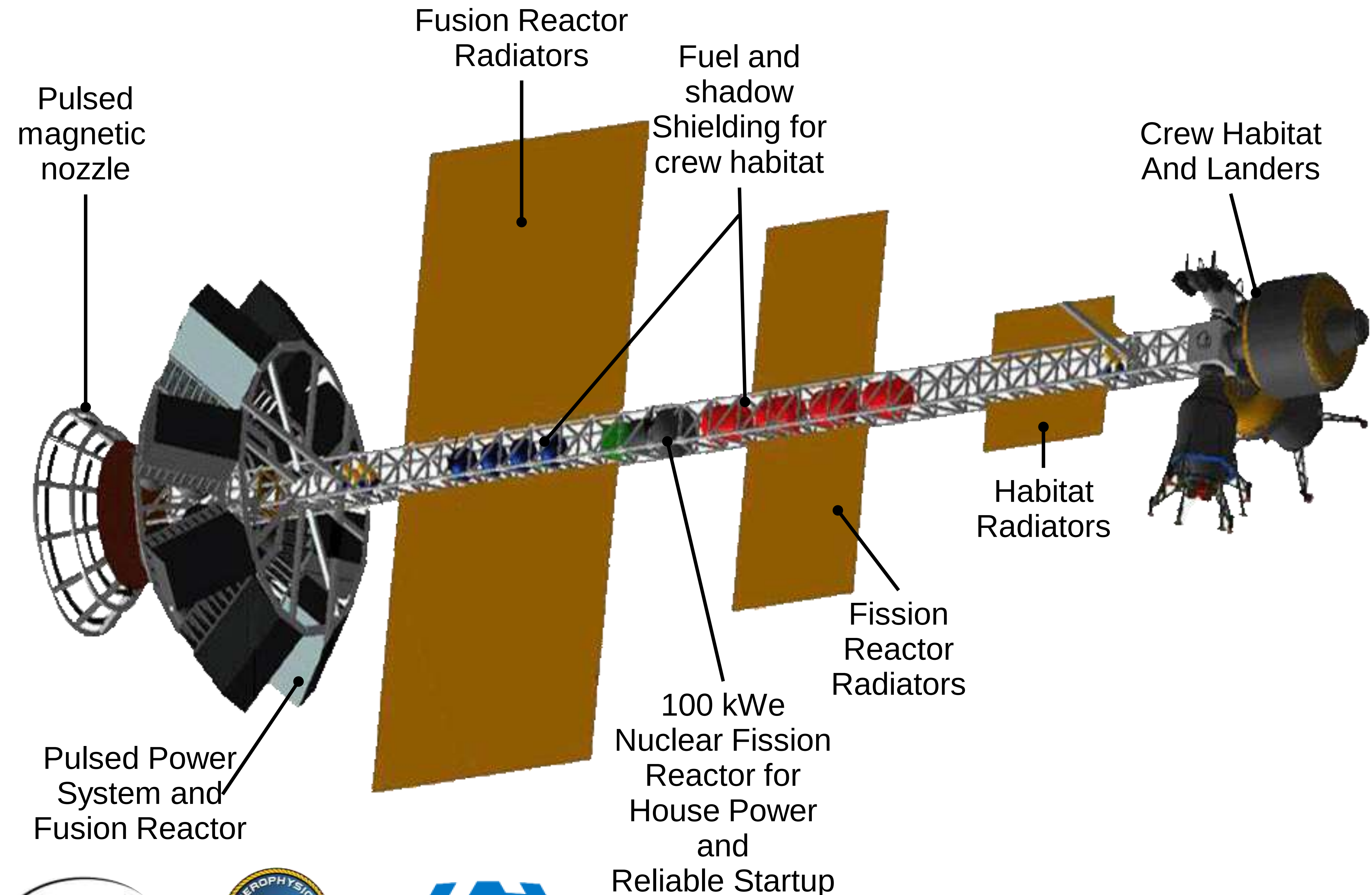


- Reactor > Yankee Stadium

- Costly Fuels

Costs per Kilogram

Tritium	**$30,000,000**
^{3}He	**$1,231,000**
^{6}Lithium	**$6,000**
Deuterium	**$4,000**



THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

NASA’s Vision is to reach for new heights and reveal the unknown, so that what we do and learn will benefit all humankind.

NASA’s Mission is to drive advances in science, technology, aeronautics, and space exploration to enhance knowledge, education, innovation, economic vitality, and stewardship of Earth.

The NASA Space Technology Mission Directorate (STMD):

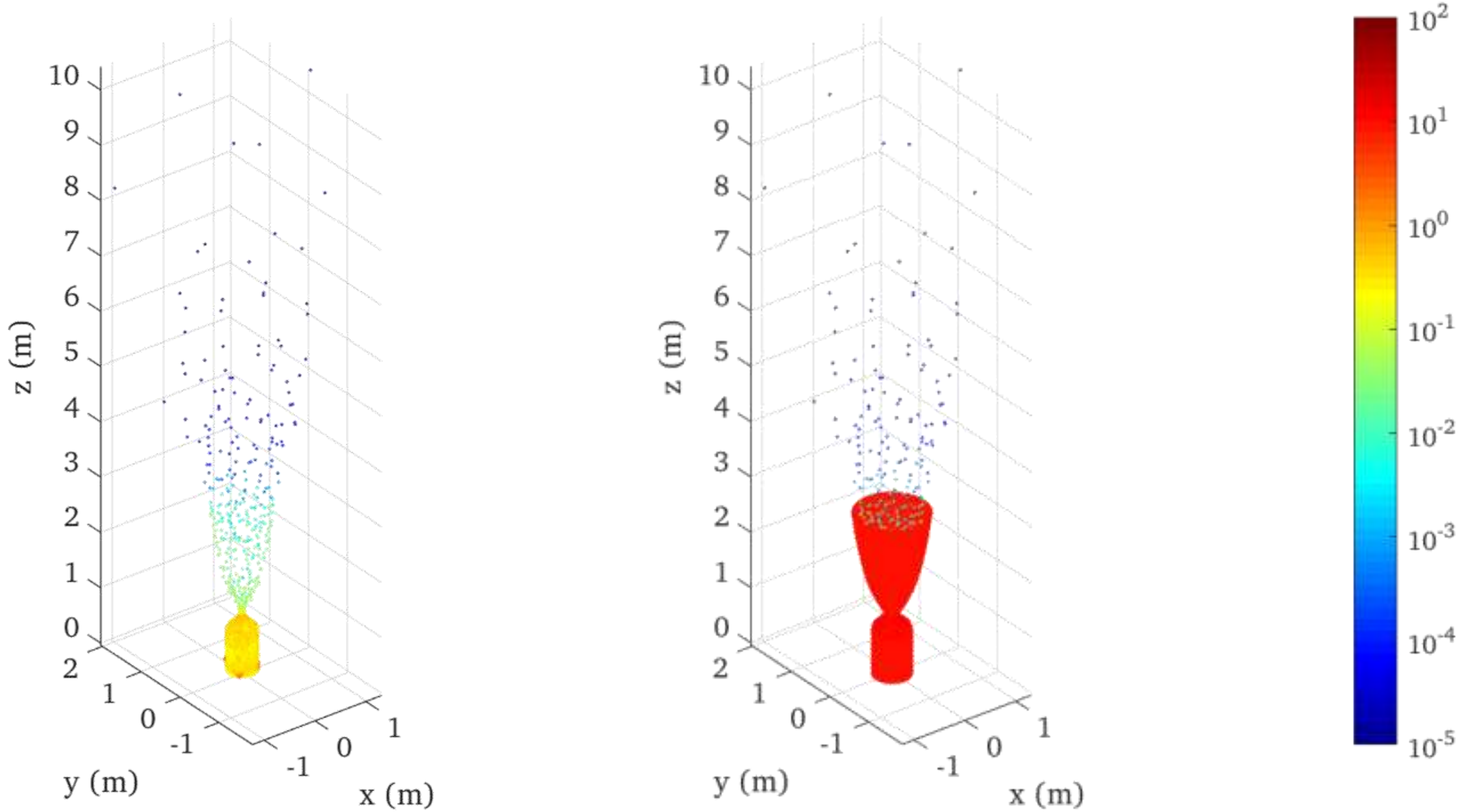
- Advances broadly applicable, transformational technology to infuse solutions into applications for which there are multiple customers
- Competitively selects technology development efforts based on technical merit
- Leverages the technology investments of other Government agency, academic, industry, and our international partners
- Coordinates with internal and external stakeholders, including academia, industry and other Government agencies
- Results in new inventions, new capabilities and the creation of a pipeline of innovators aimed at serving future national needs
- Grows the Nation’s innovation economy and creates new high-tech jobs

Our vision: To utilize a complementary and multidisciplinary team to research and advance a bimodal fission and fusion hybrid propulsion system and associated technologies to TRL 3 or higher to help fulfill the NASA STRI goal of rapid interplanetary space exploration and interstellar precursor missions.

Example of a bimodal nuclear thermal rocket

"Nuclear Thermal Propulsion (NTP): A Proven Growth Technology for Human NEO/Mars Exploration Missions," Borowski, Stanley K., McCurdy, David R., Packard, Thomas W., 2012 IEEE Aerospace Conference; 3-10 Mar. 2012; Big Sky, MT.

Pilot simulation of a 3D NERVA nozzle



Charger 1 Fusion Propulsion Facility

UAH Propulsion Research Center

Prof. R. Frederick, PhD, Director

Prof. D. Thomas, PhD, Deputy Director

https://www.uah.edu/prc

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

A. Edmondson, MBA

Research Prog. Administrator/Budget Analyst

M. Kitts, PRA; M. Nemati, OCE; J. Prince SS3

Eminent Scholar In Propulsion

Prof. P. Ligrani, PhD

Aerospace Propulsion and Systems Integration Strategic Planning

Prof. D. Thomas, PhD. Eminent Scholar in Systems Engineering

Prof. P. Collopy, PhD, Chair of ISEEM Department; Prof. S. Mahalingam, PhD, Dean of the College of Engineering

G. Karr, Principal Research Scientist VI; M. Miller, Research Scientist V

A. Aeuron, GTA

Propulsion Laboratory and Safety

Dr. D. Lineberry, PhD, Laboratory Operations

T. Hall, Test Engineer

Energy & Power Systems

Prof. P. Ligrani, PhD

J. Blackmon, PhD
P. Collopy, PhD
K. Frendi, PhD
C. Kang, PhD
S. Mahalingam, PhD
G. Nelson, PhD
S. Rani, PhD

D. Copeland, GRA; S. Marko, GRA; P. McInturff, GRA; C. Ren, GRA; Z. Ren, GRA; M. Su, GRA; M. Suzuki, GRA; S. R. Vanga, GRA

M. Anderson, UGA; A. Click, UGA; A. Miller, UGA; R. Petrimoulx, UGA; D. Ritchie, UGA

Fusion Propulsion & Power

Prof. J. Cassibry, PhD

R. Cortez (RI)
W. Seidler, PhD

T. Englestad, PTGS
P. Giddens, OCE
D. Hewitt, PTGS
S. Kumar, GTA
M. Rogriguez, PTGS
K. Schillo, GRA
R. Tackett, PTGS
B. Winterling, GRA

Plasmas & Combustion

Prof. G. Xu, PhD

J. Cassibry, PhD
K. Frendi, PhD

R. Dextre, GRA
R. Gott, GTA
P. Salvador, GRA

N. Latham, UGA
N. Mann, UGA
W. Manneschmidt, UGA
R. Nakano, UGA
T. Yamauchi, UGA

Computational Modeling

Prof. S. Rani, PhD

F. Ewere, PhD (Lecturer)
K. Frendi, PhD
C. Kang, PhD
S. Mahalingam, PhD
S. Ravindran, PhD
B. Shotorban, PhD

V. Rani, GTA
Wilson, GTA
V. Keshava Rao Ravulapati, SS5

Aerospace Materials & Structures

Prof. G. Nelson, PhD

K. Hazeli, PhD
M. Lin, PhD
J. Schneider, PhD
G. Wang, PhD

B. Bahramibabamiri, GRA; J. Buckley, GRA; R. Chow, GRA; J. Indeck, GRA; D. Kodali, GTA; P. Morrison, SS5

E. Andrew, UGA
G. Andrew, UGA
J. Floyd, UGA
M. Frederick UGA
A. Minor UGA

Propellants & Energetics

Prof. R. Frederick, PhD

J. Baird, PhD
M. Banish, PhD
J. Blackmon, PhD
D. Lineberry, PhD
G. Xu, PhD
S. Williams, OCE

C. Blankenship, PTGS; S. Bluestone, PTGS; C. Freeman PTGS; A. Hiatt, GRA; D. Jones, GRA; S. Kathalagiri Vasantha Kumar, GTA; R. Pereira, GTA; I. Ranade, GTA

J. Schroder, UGA

Propulsion System Technology Test-bed

D. Lineberry, PhD

B. Landrum, PhD
P. Ligrani, PhD
G. Wang, PhD

A. Bower, GRA; V. Braswell, OCE; A. Patel, GRA; R. Hicks, GRA; E. Tingley, GTA

J. Agnew, UGA; D. Battle, SS4; J. Bigalow, MAE 490; B. Chubb, MAE 490; D. Corey, UGA; B. Ha, MAE 490; D. Hajian, MAE 490; J. Hobbs, MAE 490; J. Hunter, MAE 490; N. Long, MAE 490; F. McKee, MAE 490; W. Pico, MAE 490; E. Powers, MAE 490; E. Zimovan, MAE 490

GRA=Graduate Research Assistant; GTA=Graduate Teaching Assistant; MAE 490=Student in MAE 490; OCE=On-Call Employee; Post-Doctoral Fellow; PTGS=Part-Time Graduate Student; PRA=Propulsion Research Assistant; RI=Research Institute; SS3=Student Specialist III; SS4=Student Specialist IV; SS5=Student Specialist V; UGA=Undergraduate Assistant

09/13/2017

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

UAH Fusion Propulsion Consortium

Recent milestones for making Charger 1 operational include the oil and water deionization systems

Oil system

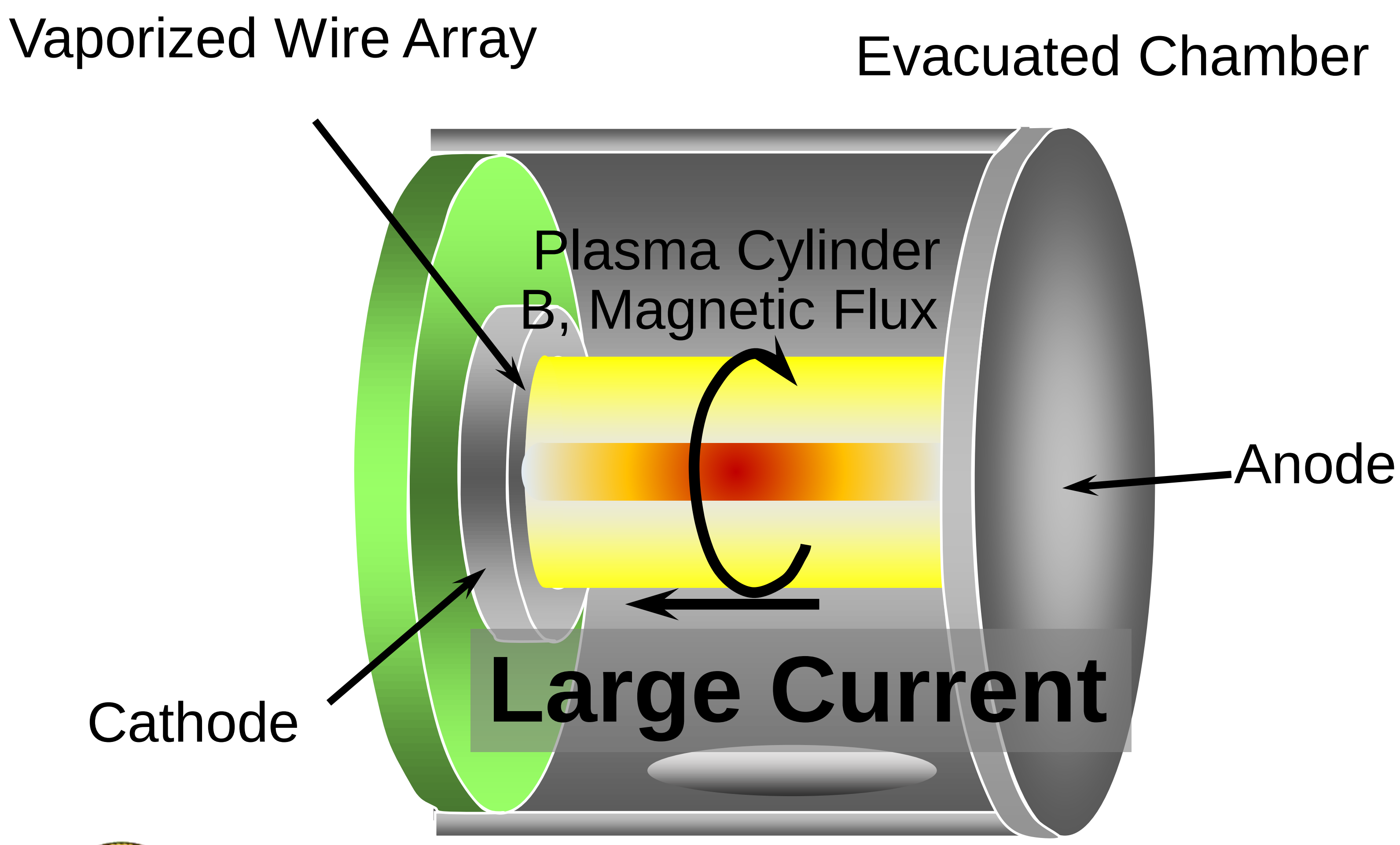
Water deionization system

Trigger system
(not shown, approximate placement)

Spark gap switch system

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

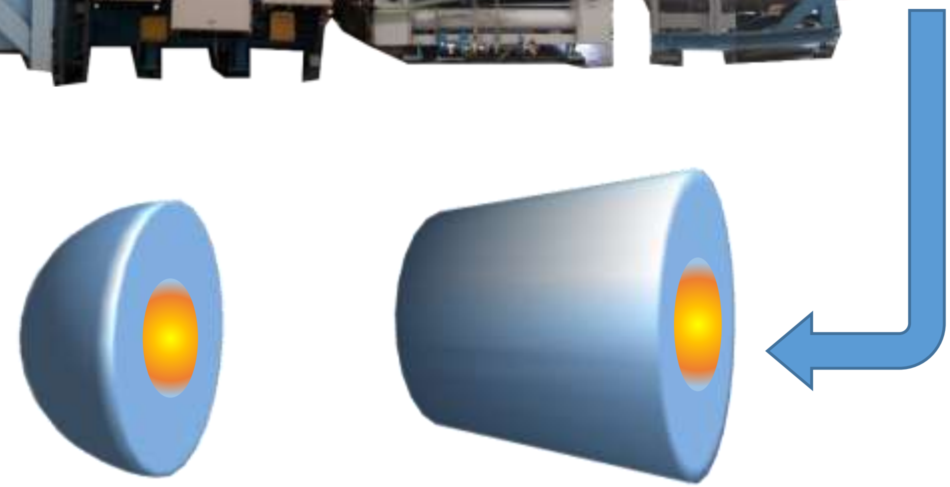
Notional Z-Pinch Target

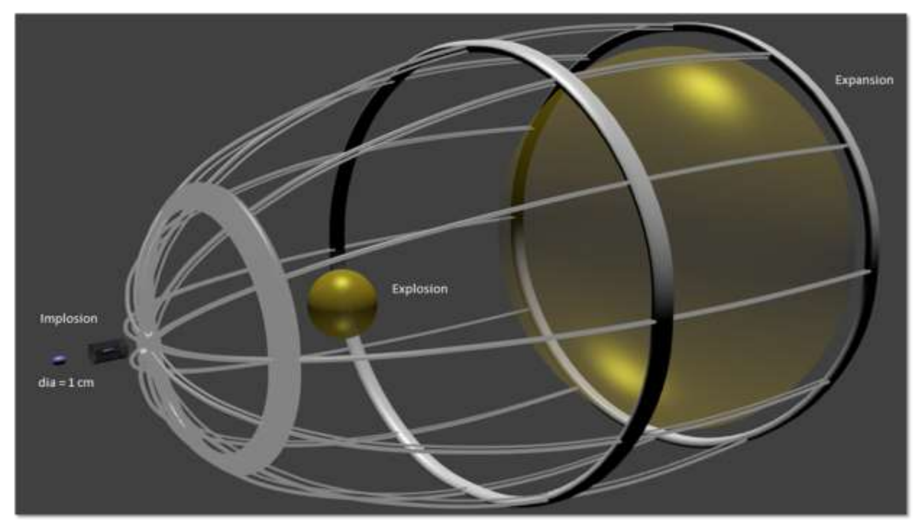


THE UNIVERSITY OF
ALABAMA IN HUNTSVILLE

Pulsed Fission Fusion Hybrid (PUFF)

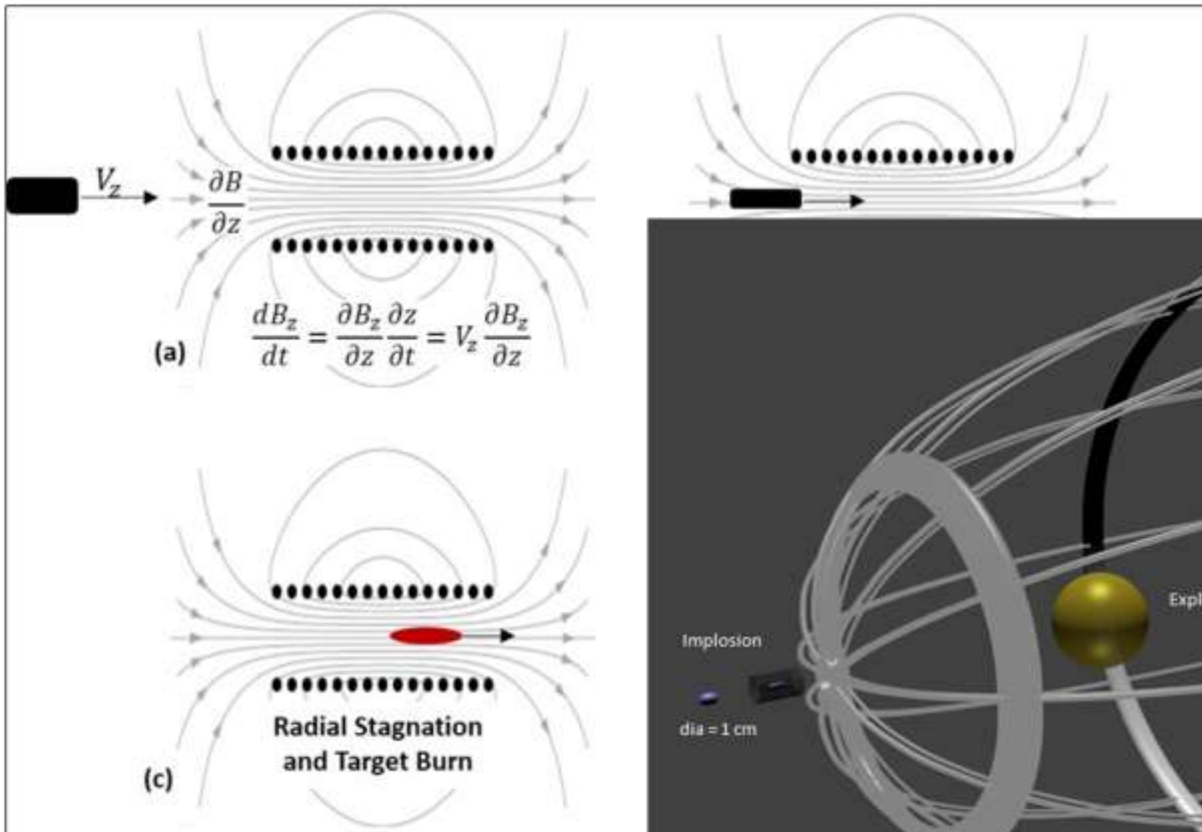
- Fuel
  - Fission liner (^{238}U ^{232}Th)
  - ^{6}Li D or D-T center
  - Initial neutron source
    - Spontaneous (AmBe)
    - Fusion (DT, DD)
- Geometry
  - spherical
  - Cylindrical
- Physics models required
  - Radiation/matter interactions
  - Fast neutron fission
  - Electromagnetic fields
  - Equations of state with ionization and compression of solids

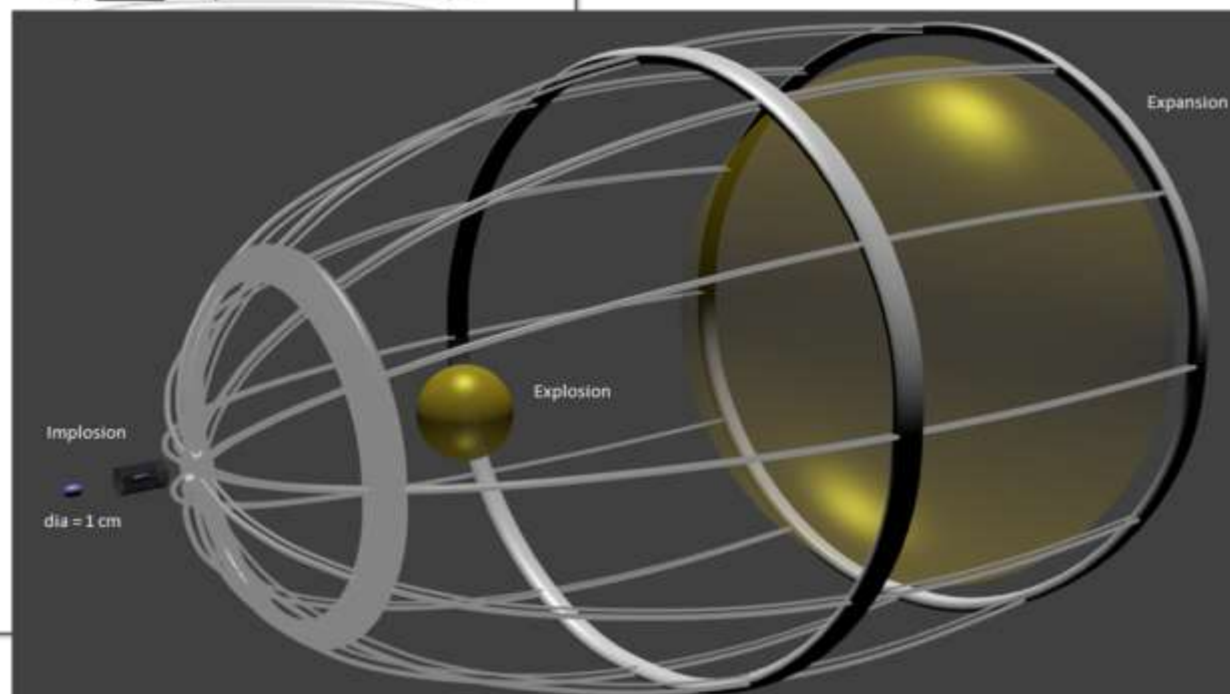




THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

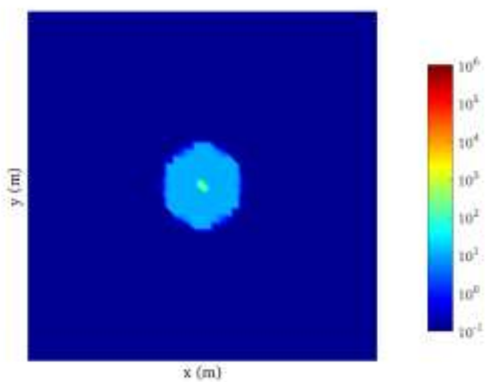
Gradient Field Imploding Liner Fusion Propulsion



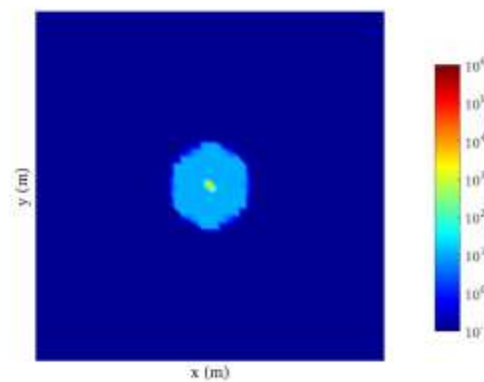


Temperature slice, center of target, t=0 ns

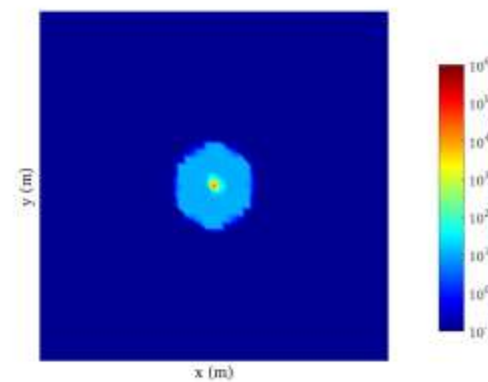
T = 2 keV



T = 5 keV



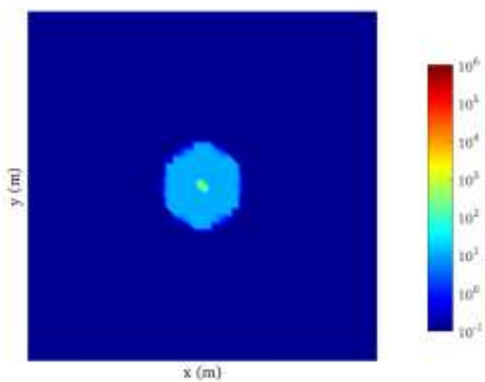
T = 10 keV



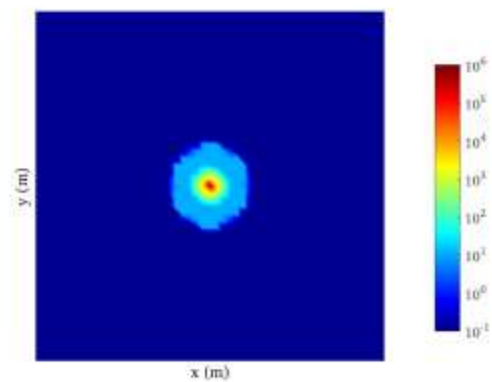
THE UNIVERSITY OF
ALABAMA IN HUNTSVILLE

Temperature slice, center of target, t=50 ns

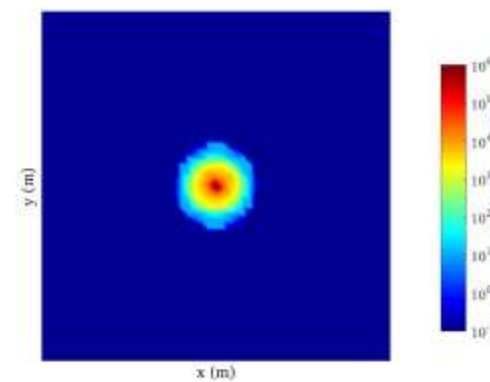
T = 2 keV



T = 5 keV

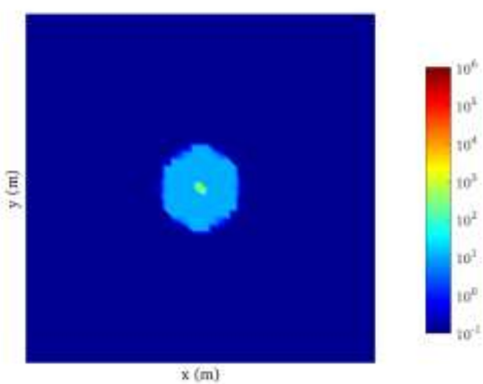


T = 10 keV

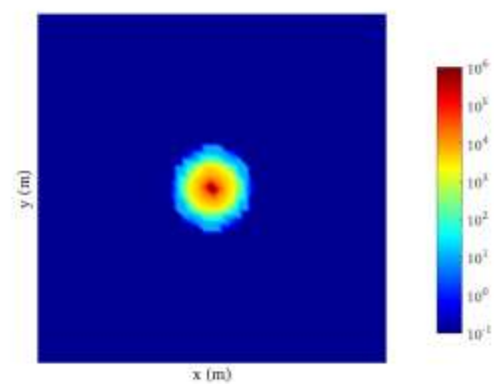


Temperature slice, center of target, t=100 ns

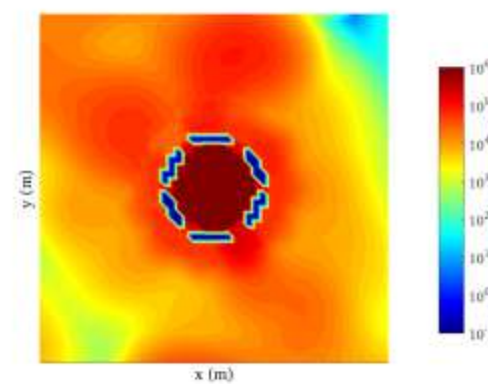
T = 2 keV



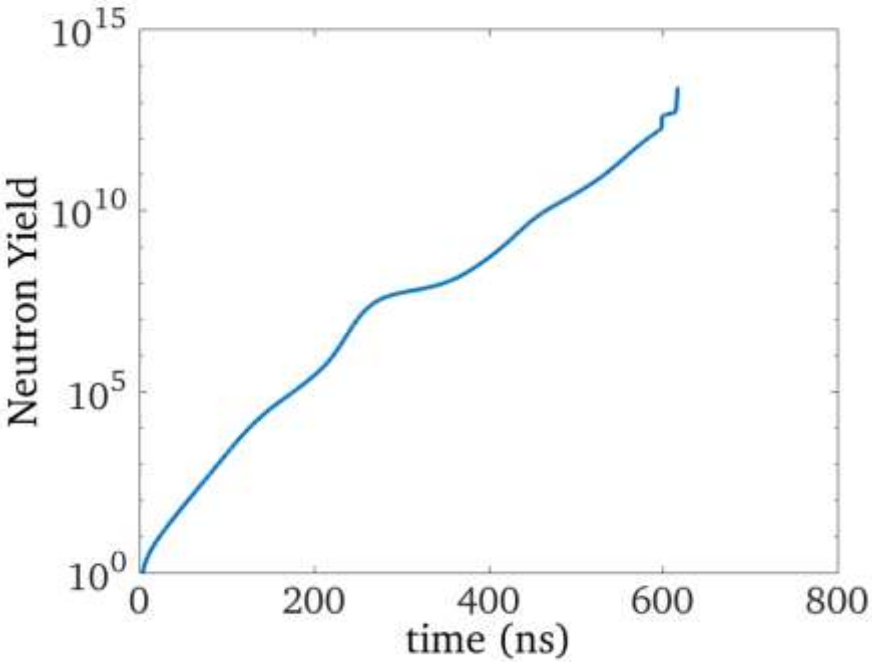
T = 5 keV

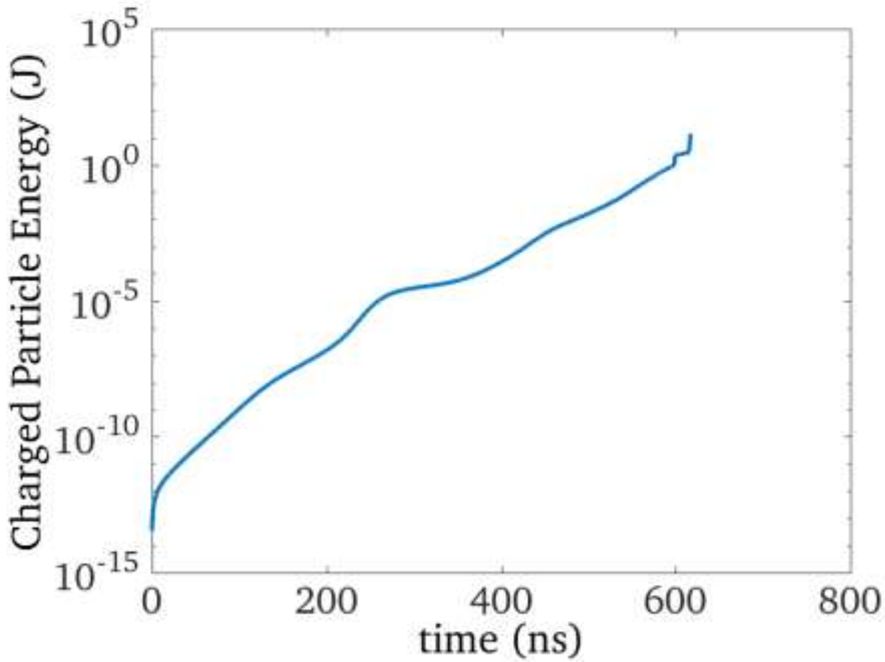


T = 10 keV



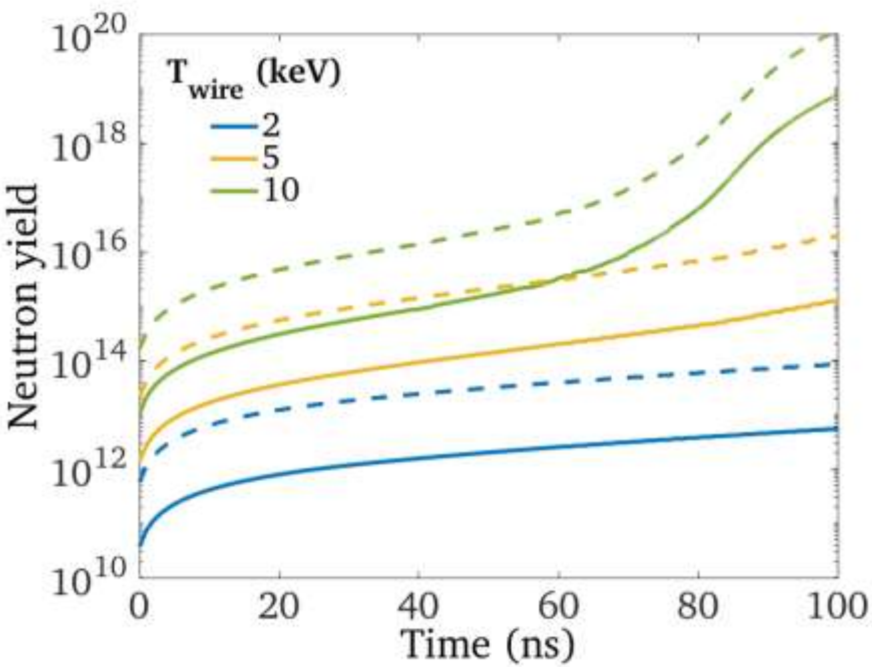
Neutron yield and charged particle energy yield vs time, prior to code crashing

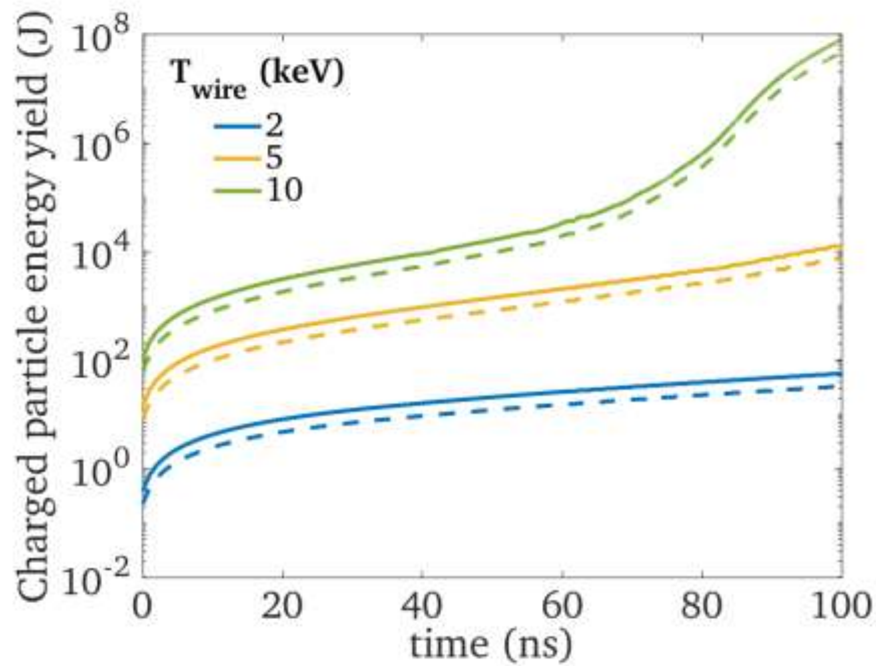




THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

High temperature wire leads to burn in secondary fusion liner at 70 ns assuming 10 keV ^{6}Li D wire temperature. Fission and fusion reactivity are tightly coupled.





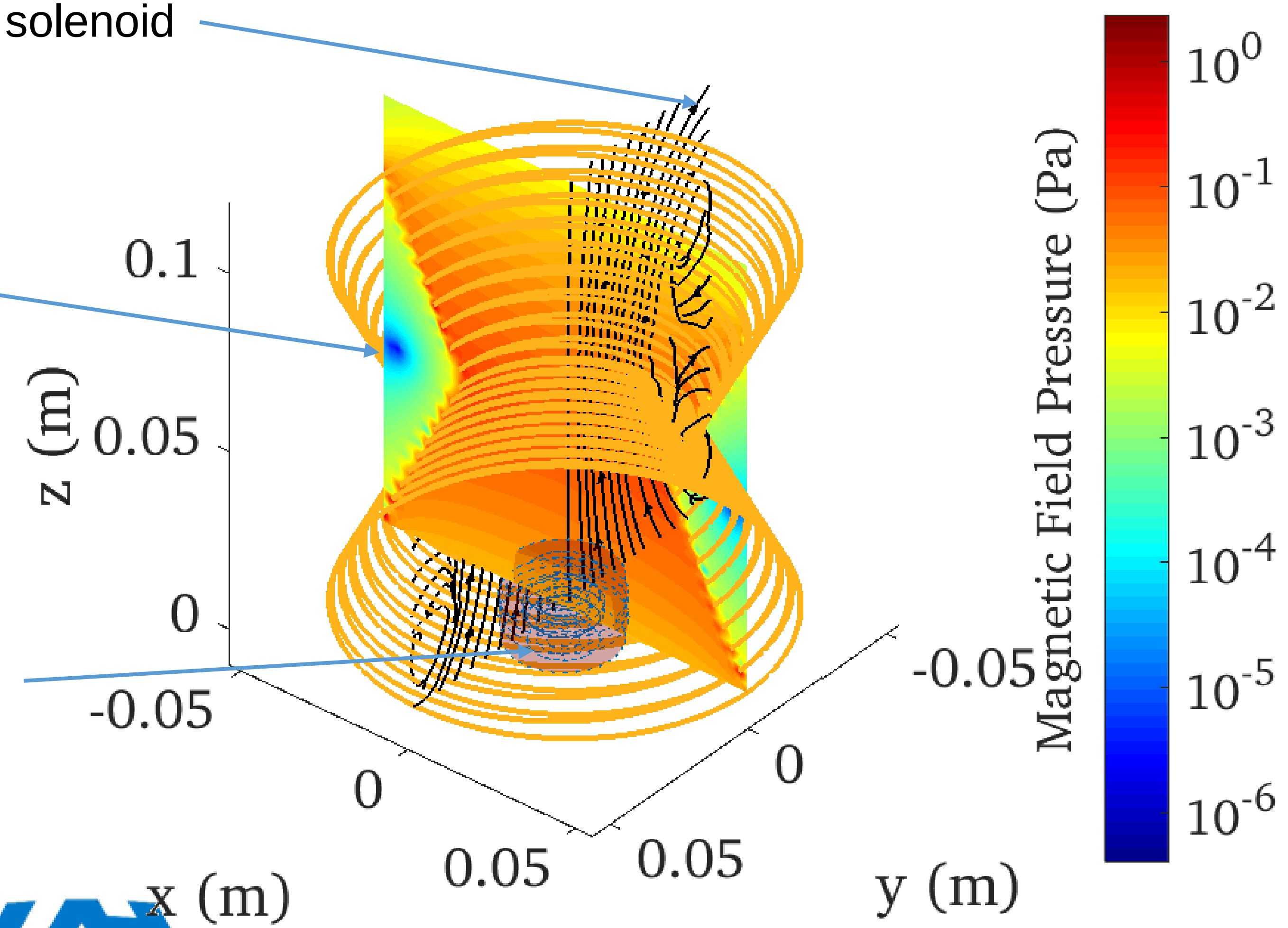
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Gradient Field Fusion Propulsion system simulation

Magnetic field lines inside solenoid

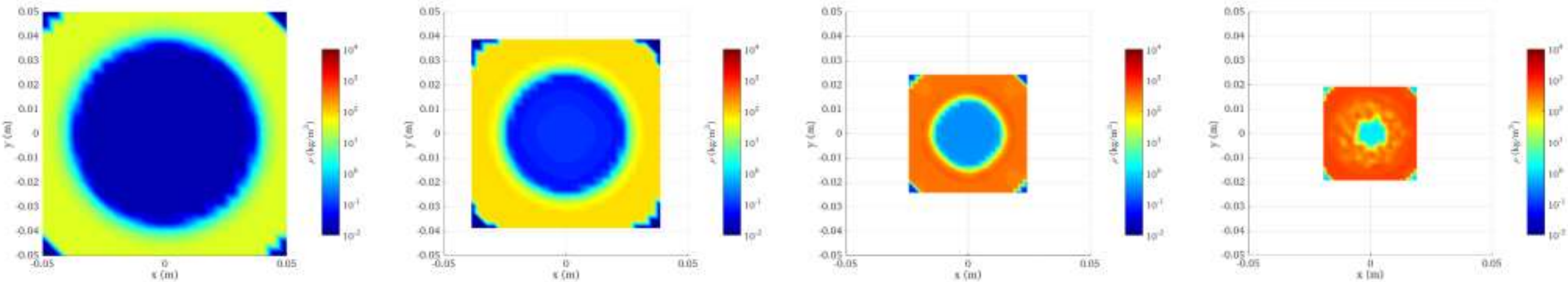
Magnetic field pressure

Fuel pellet entering mouth
Of nozzle at several km/s



Mass Density

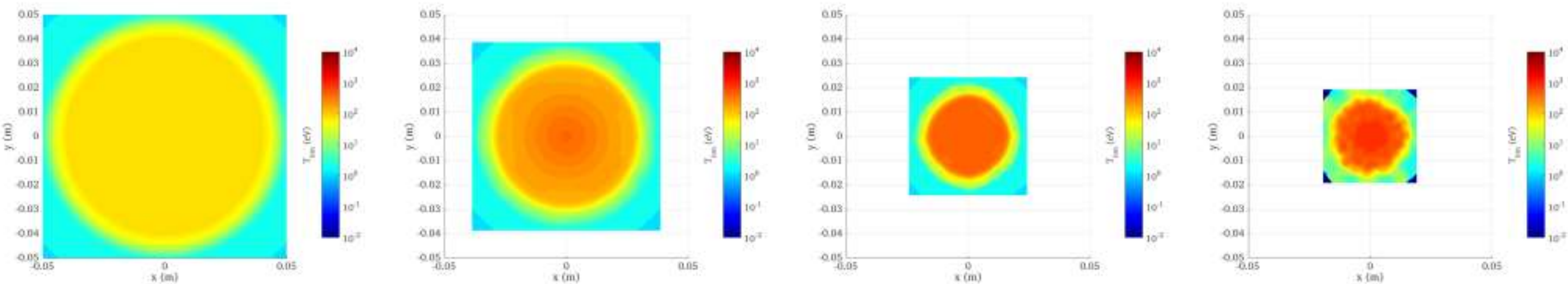
t = 0 ns **t = 250 ns** **t = 500 ns**

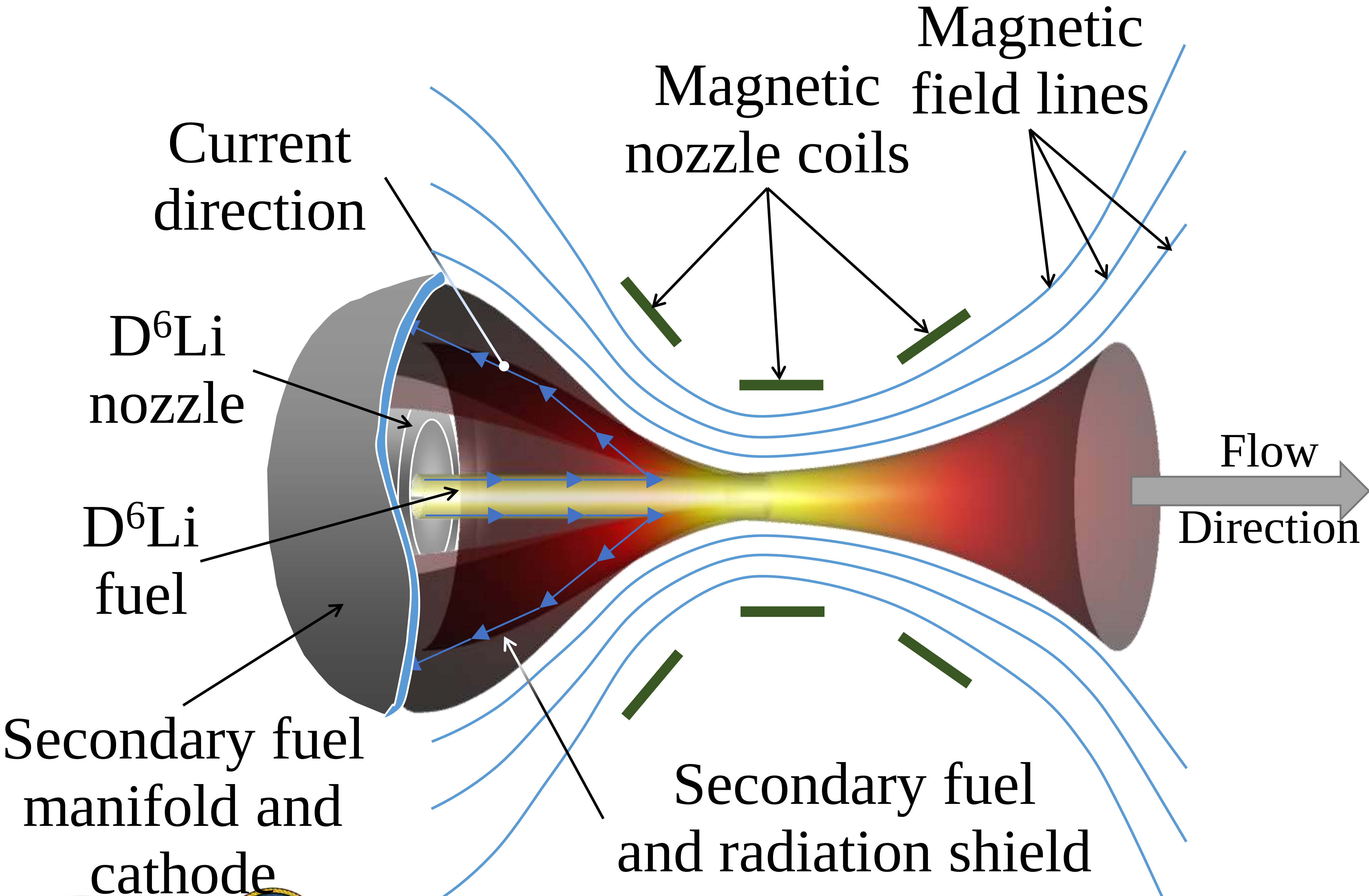


THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Ion Temperature

t = 0 ns **t = 250 ns** **t = 500 ns**

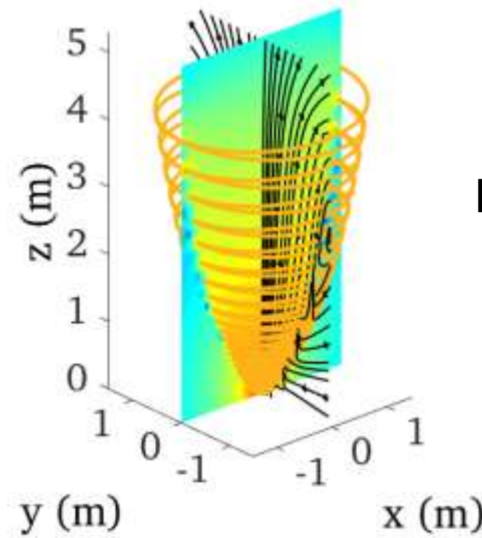




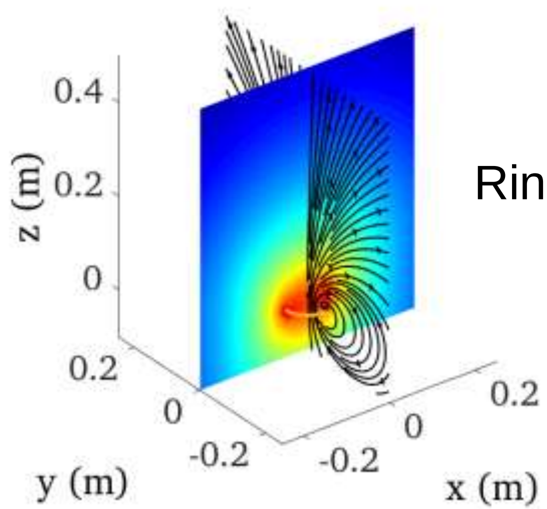
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Simulation attempts in magnetic topology

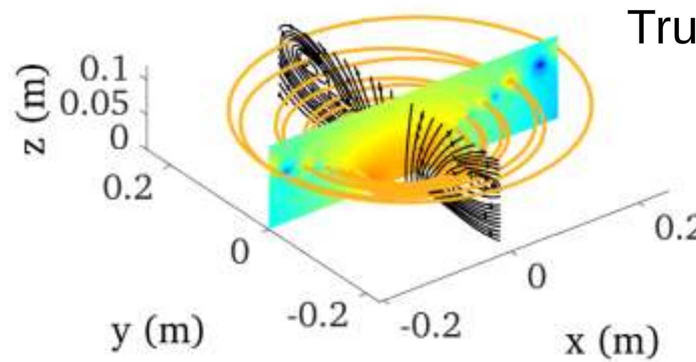
- Solenoidal winding variations
  - NERVA nozzle shape
  - Ring
  - Bell (like end of trumpet)
- Initial plasma placement
- Key parameter is finding topology that gives jxB Lorentz force in axial direction during expansion



NERVA

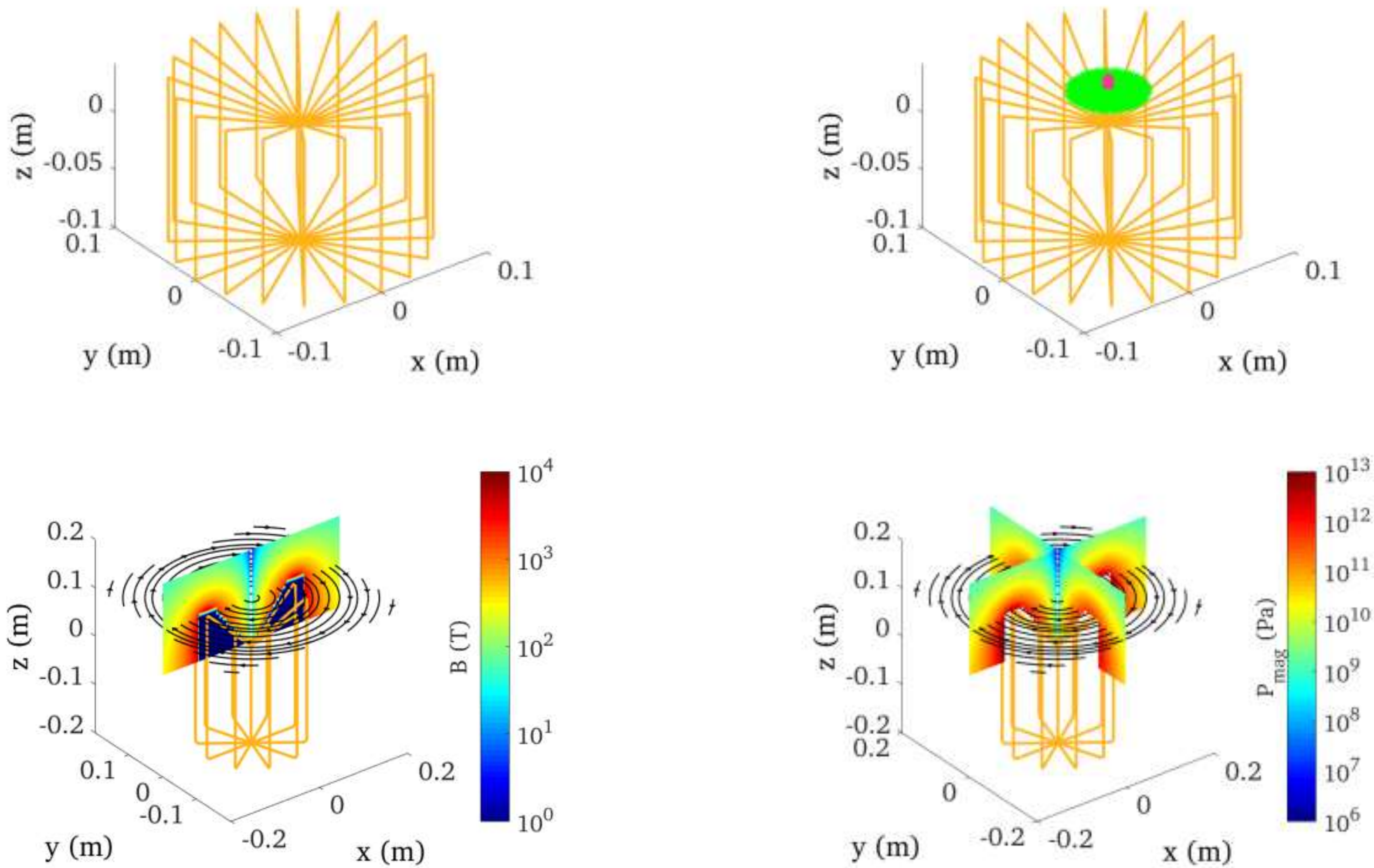


Ring



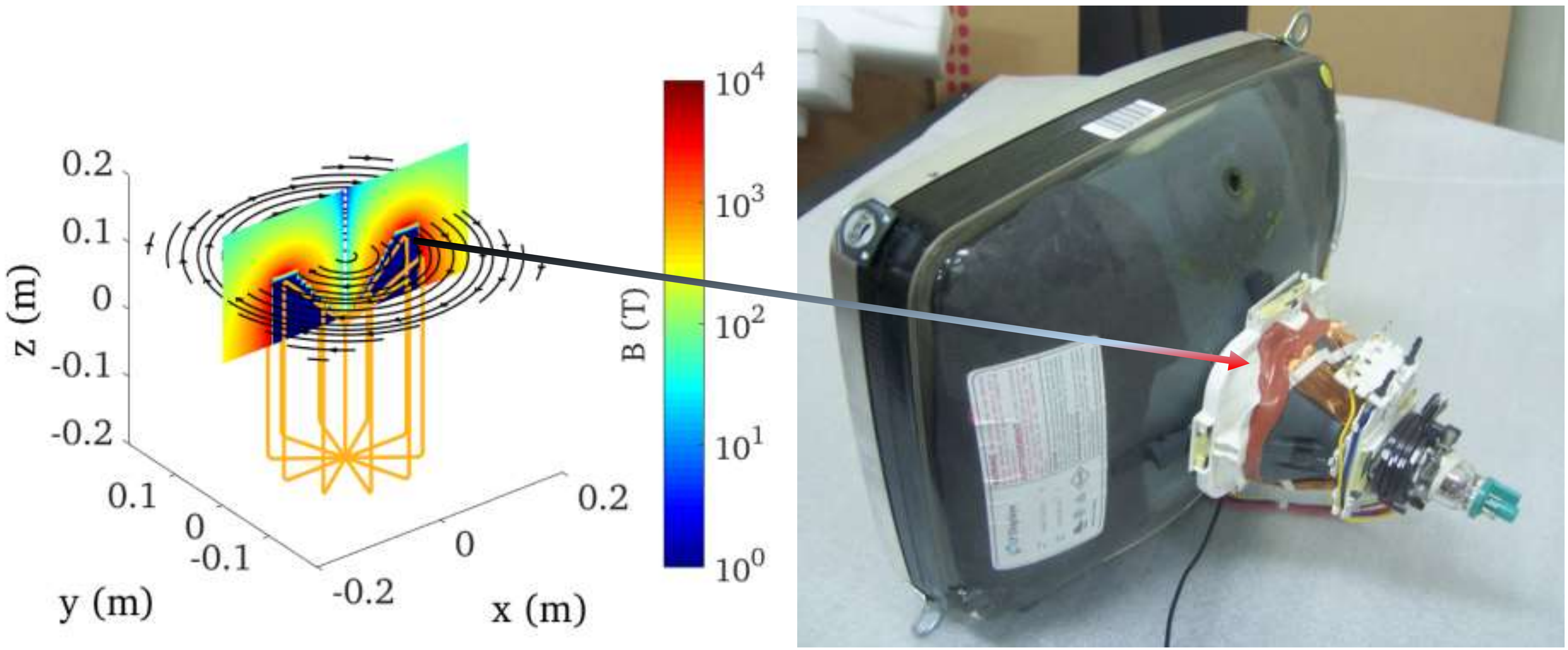
Trumpet

Departure from solenoid to longitudinal windings provided positive results because of nearly azimuthal magnetic field generated.



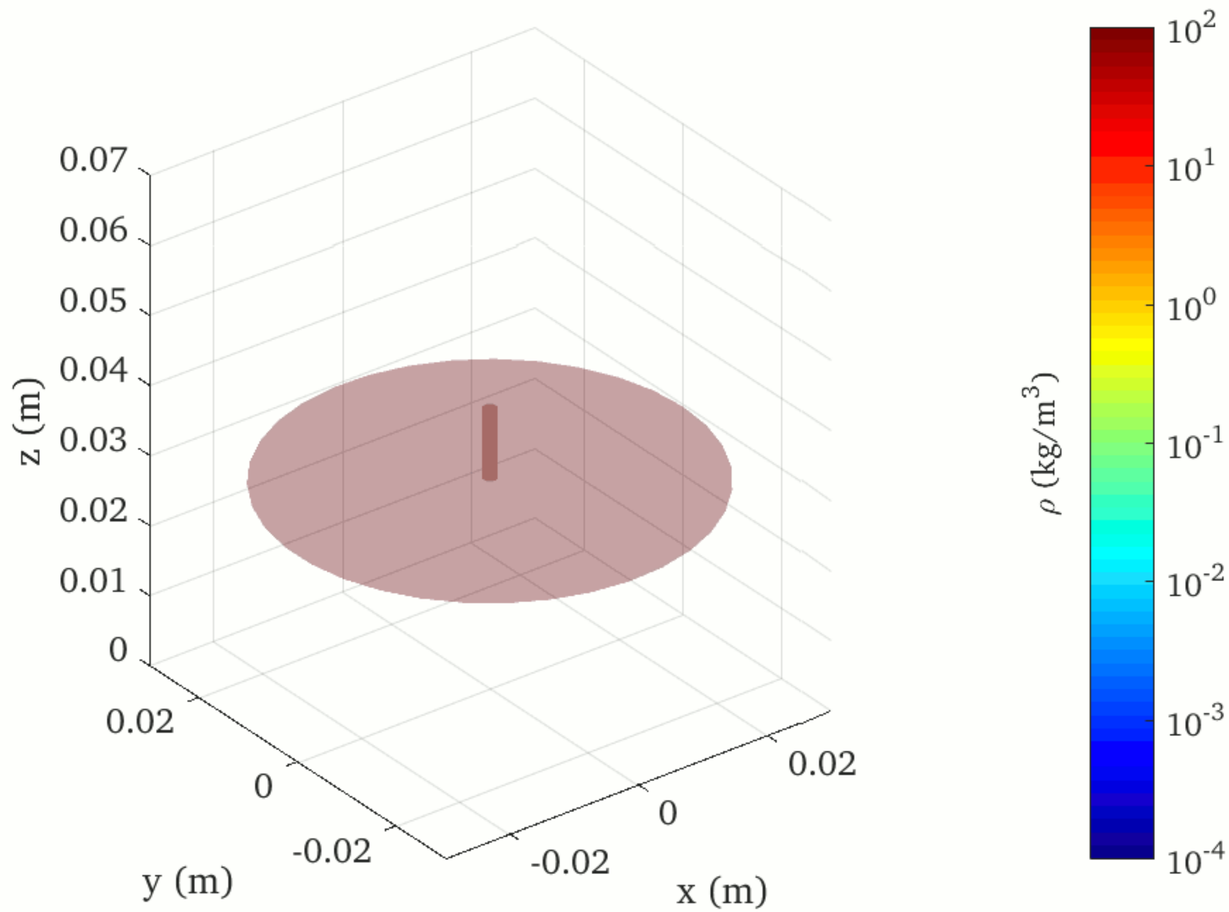
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Anything new was probably invented in the last century…



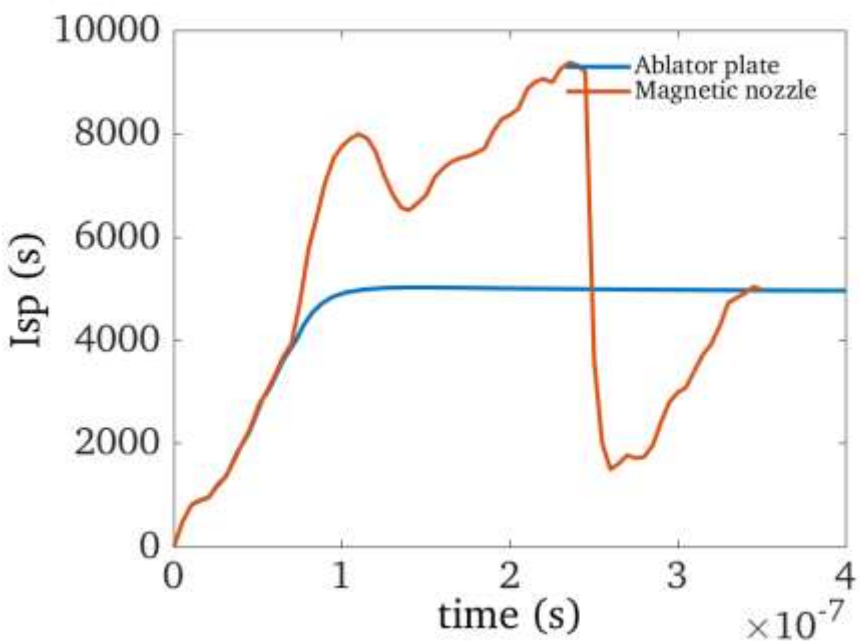
Early results for a 1 keV DT plasma

- Thermal expansion against plate provides most of the impulse
- Induced current on the surface excludes the externally provided flux from the nozzle and partially redirects the flow



Comparison of pure ablator plate and with nozzle

- Presence of field provides additional redirection of thermally expanded plasma
- Improvements are seen against pure ablator plate with no field
- At 250 ns, the circuit model crashes (next task is to explore why)
- Rapid tapering off of Isp with time during expansion caused by radiation cooling



Summary of vehicle performance parameters for very deep space missions

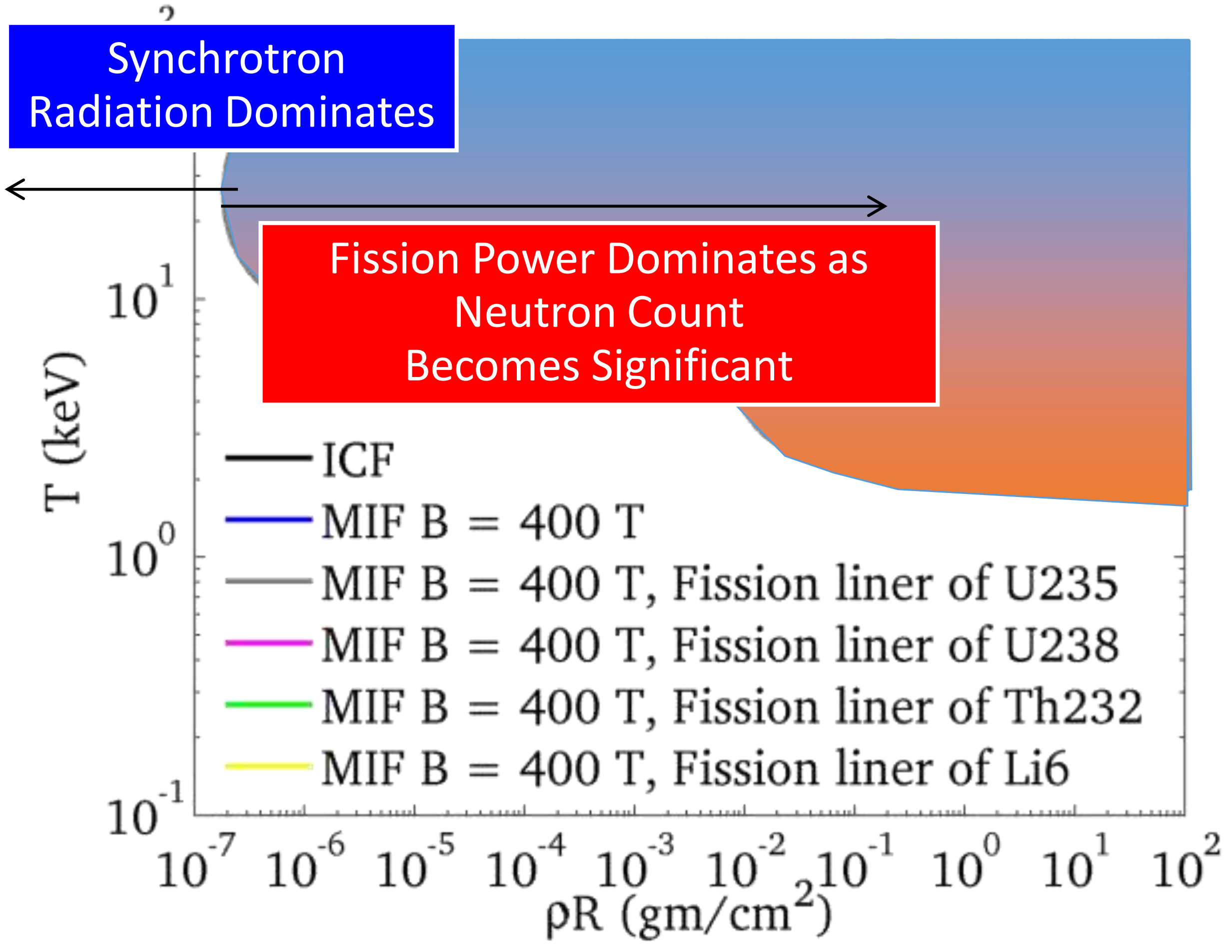
Destination	Trip time (years)	Isp (s)	IMLEO (metric tons)	Thrust (N)	Shot frequency (1/s)	Mass flow rate (mg/s)	ΔV (km/s)
Gravitational Lensing	10	9.4×10^4	15.3	0.66	2.9	0.72	392
Alpha Centauri	269	2.7×10^5	1000	1.39	8.8	0.48	7,280

Concluding remarks

- Fusion and Fission/Fusion hybrid concepts being studied to enable rapid interplanetary space flight for human piloted and science missions.
- The need for reliable restarts requires a nuclear electric system for deep space travel
- The low thrust compromises trip times due to the slow spiral out of Earth's gravity well
- A bimodal approach has been proposed leveraging high thrust from an NTP system for rapid departure and high specific impulse for rapid interplanetary space travel

THE UNIVERSITY OF
ALABAMA IN HUNTSVILLE

Fusion Power Balance



- Parameter space for ignition
- Greatly broadened with embedded magnetic field
- Marginally improved with ^{6}Li and thorium liners
- Significantly enhanced with uranium liners (^{235}U and ^{238}U)

Why Send Humans to Explore Other Planets? (Additional arguments made by Bill Gerstenmeier)

- Knowledge
  - Human exploration inspires people to seek knowledge
  - Through scientific discovery we increase our understanding of the world
- Economic Growth
  - Creation of industries
  - Job growth
  - Demand for a highly skilled workforce
- A Better Future
  - Advancing American leadership
  - Creating a path for peace, diplomacy, and global cooperation