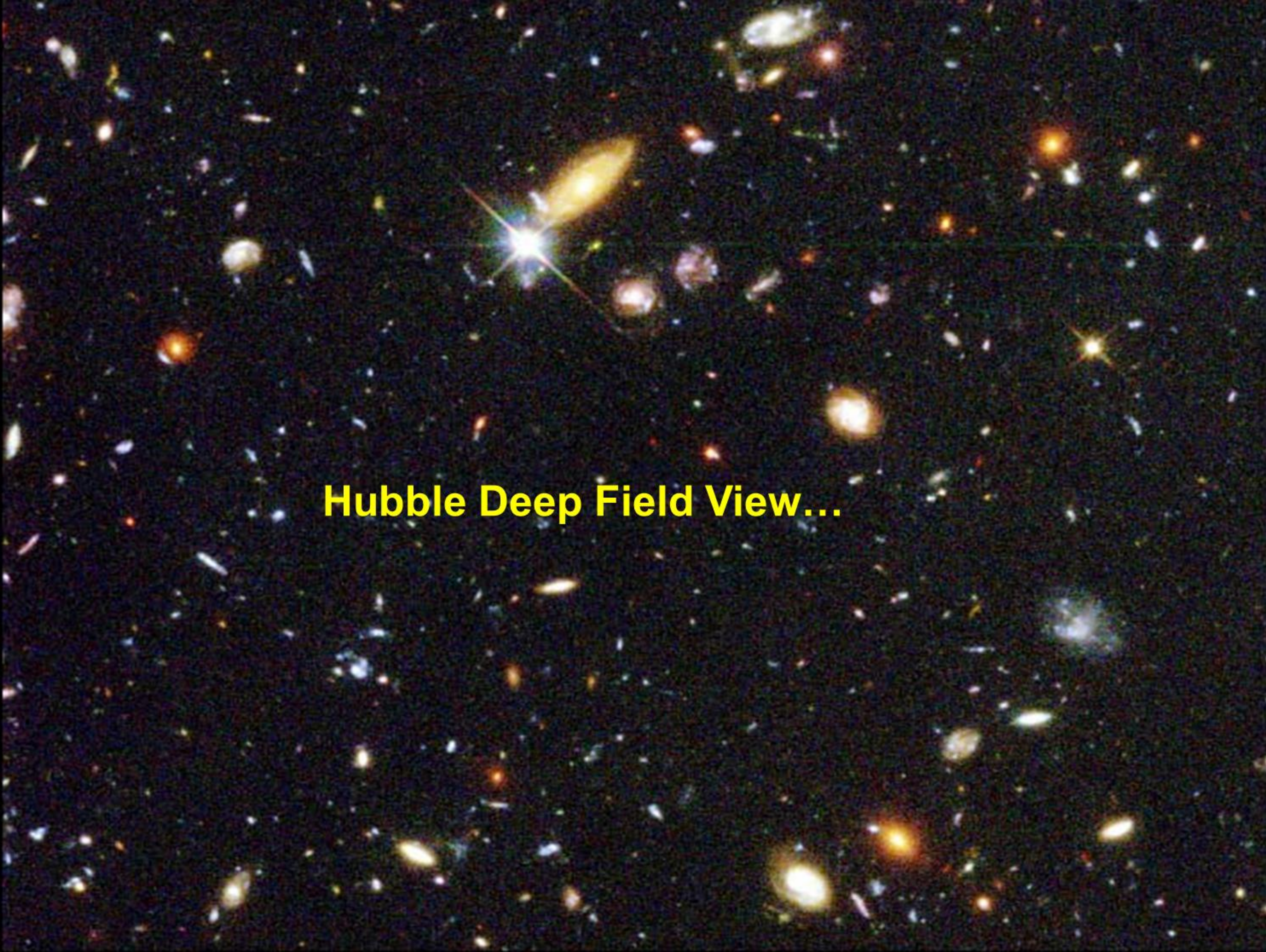
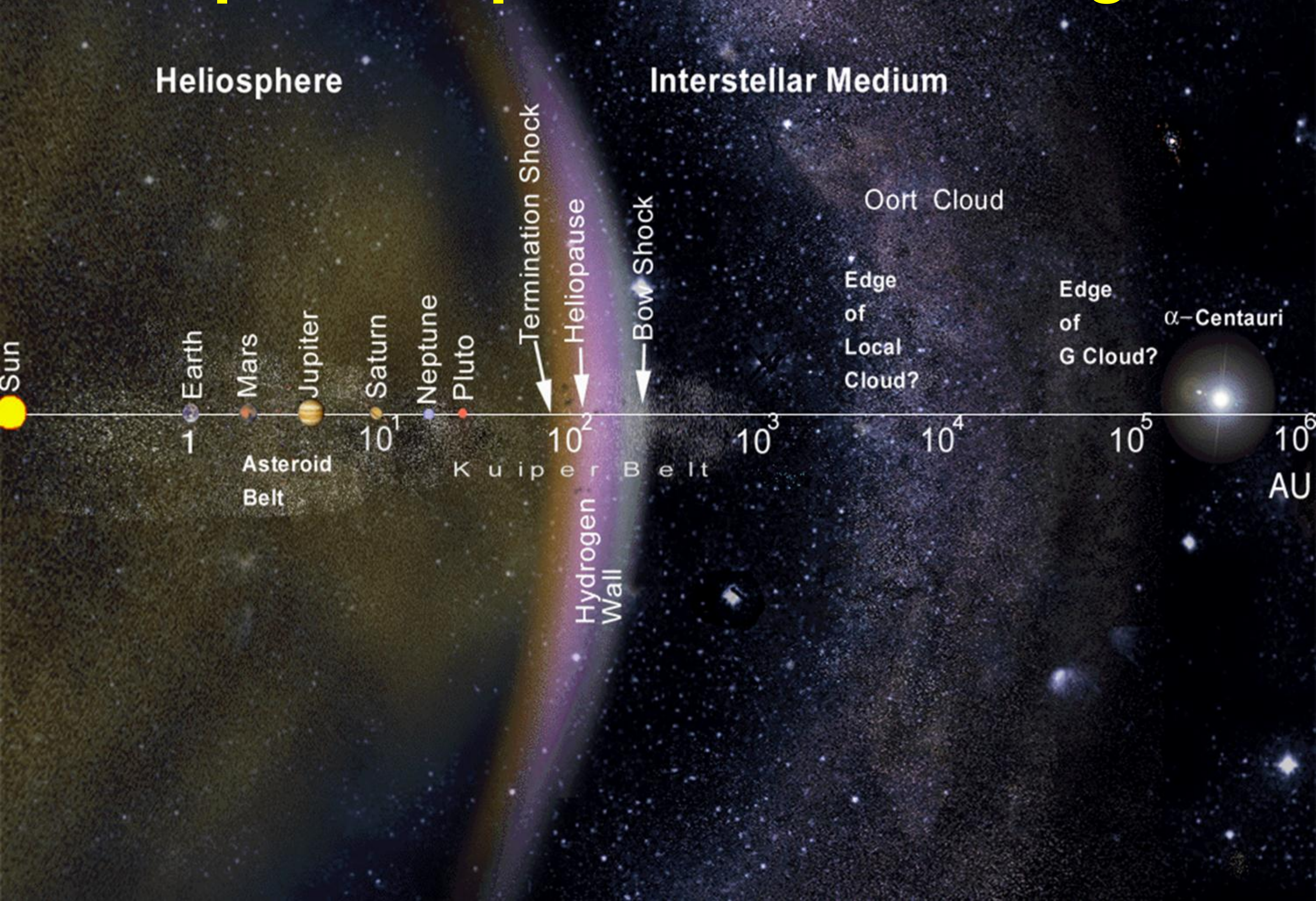
ADVANCED SPACE PROPULSION

Harold P. Gerrish Jr.
George C Marshall Space Flight Center


Hubble Deep Field View…

The Space Exploration Challenge . . .



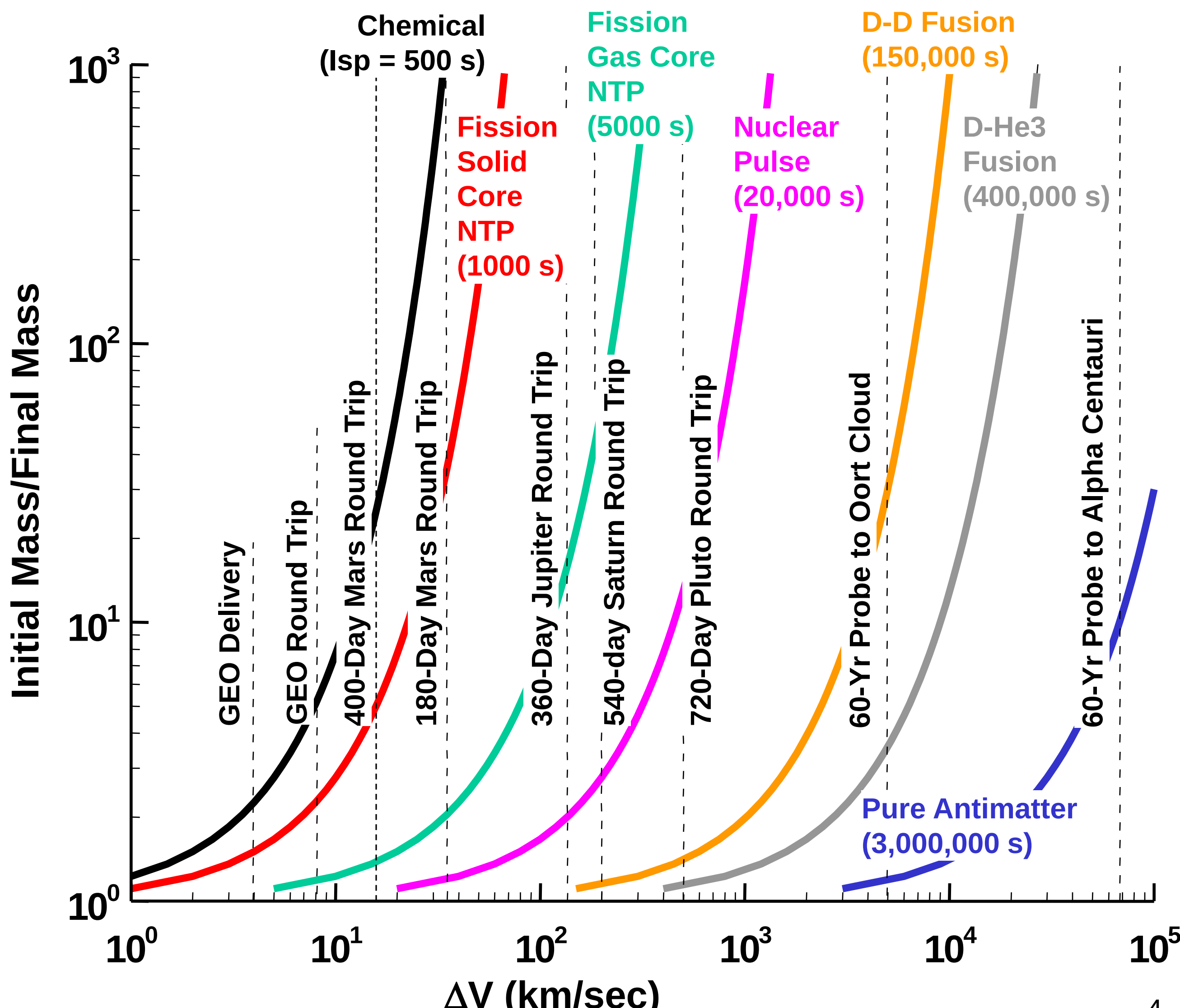
Vehicle Momentum Transfer

- **High Capability Propulsion**
  - High Specific Impulse (Isp)
  - Moderate-High Specific Power (Thrust/mass)
- **Enables high ΔV missions**
  - More rapid interplanetary flight
  - Science missions beyond solar system
- **Reduces propellant mass and/or increases mass margins**

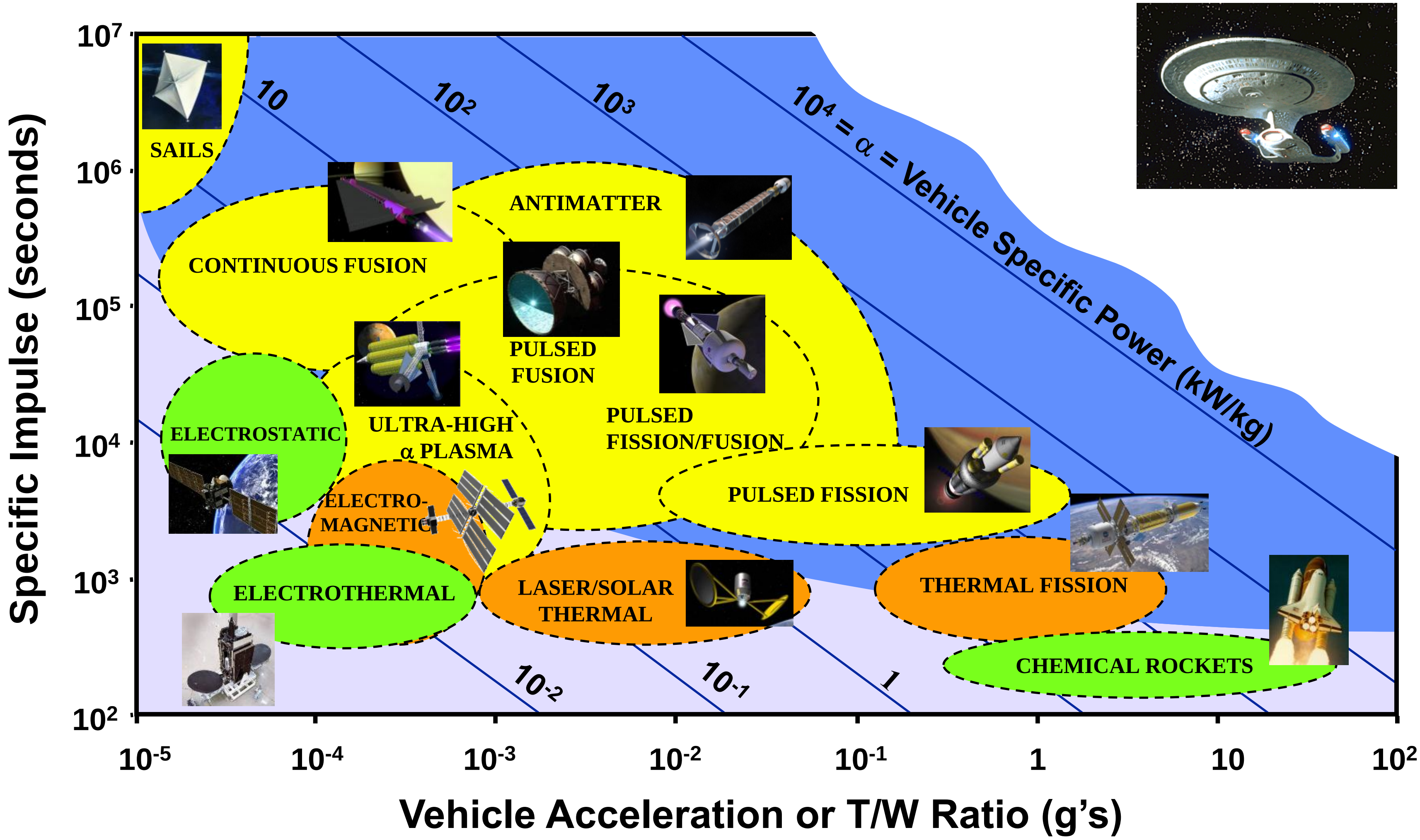
$$Isp_{max\ ideal} = \frac{\sqrt{2 \cdot Specific\ \ Energy}}{g}$$

Applicable only for non-relativistic exhaust velocities (g•Isp ≤ 0.1c)

Spacecraft Mass Ratio as Function of ΔV (Mission) for Different Propulsion Technologies



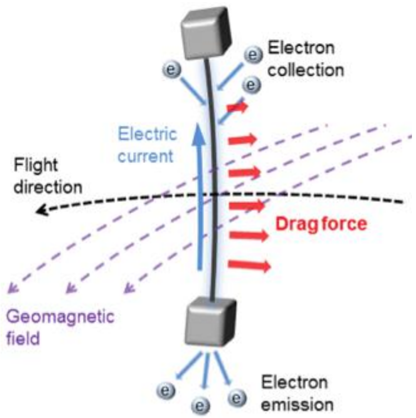
Capabilities of Candidate Propulsion Concepts



Unproven Technology (TRL 1-3) Demonstrated Technology (TRL 4-6) Operational Systems (TRL 7-9)

Propellantless-Tethers

Electrodynamic Tether Operation

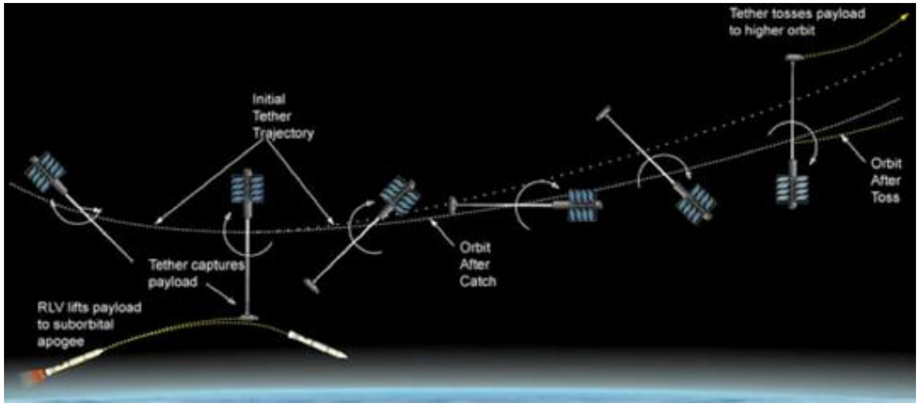


General EDT Schematic
(Drag/Power Generation Mode)
(IEPC-2001-213)

JAXA ED Tether Flight in 2010
(AIAA-2011-6503)

Motion of conducting material through magnetic field produces an electromotive force (EMF) voltage that drives an electrical current. The interaction of this current with the magnetic field produces a drag force. To produce a boost force, a high voltage power supply drives the current in the opposite direction, overcoming the motion-induced EMF. Electrons collected and emitted on opposite ends.

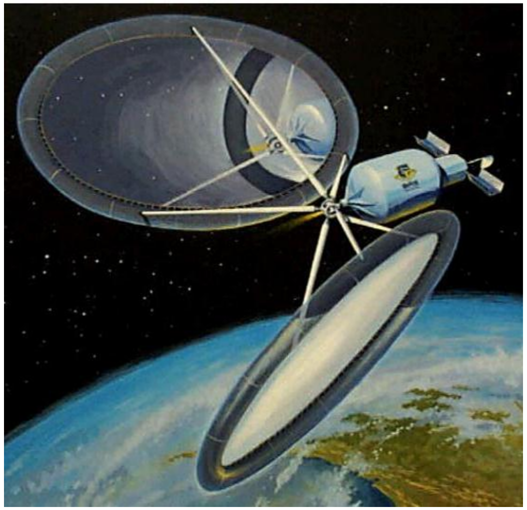
Momentum Exchange Tether Operation



General Momentum Exchange Tether Operation
(Courtesy of Tethers Unlimited)

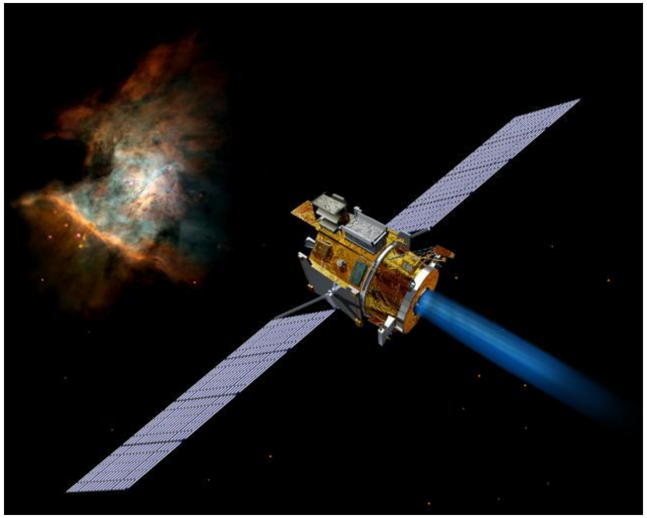
Long tether and payload are deployed from end with larger mass to either an increased or decreased altitude. Payload is “pulled” to a velocity that is different from that required to stay in its orbit. When released, the payload moves along a different orbit. Rotating the tether can increase the orbital change.

Use of Solar Energy



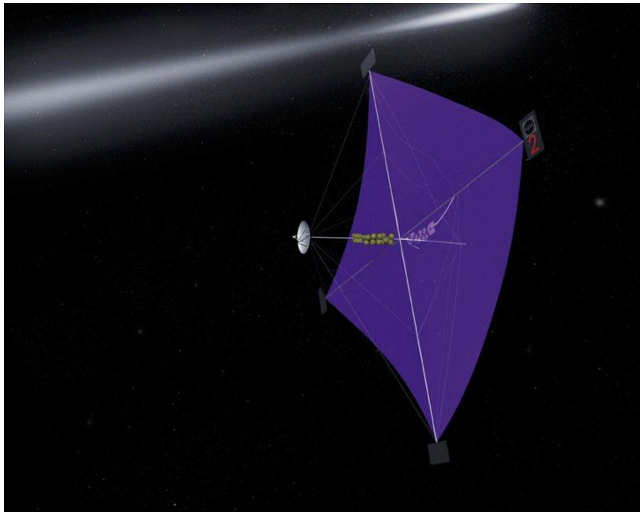
Courtesy Air Force Research Lab

Solar Thermal Propulsion



Courtesy NASA

Solar Electric Propulsion



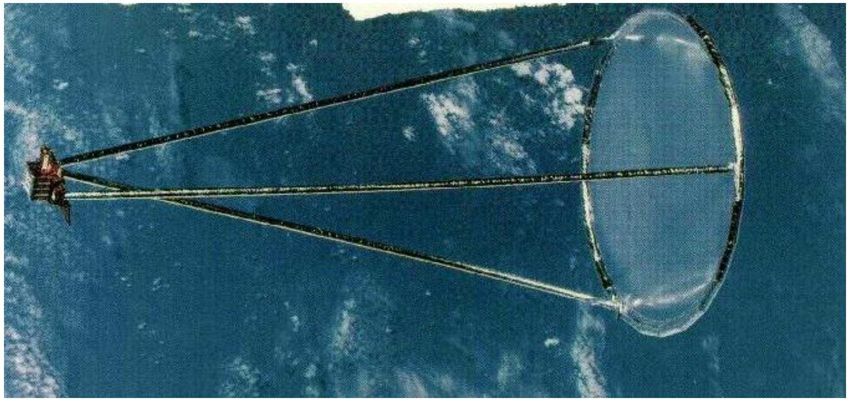
Courtesy NASA

Solar Sails

Around 1 AU, solar flux intensity is ~1400W/m2

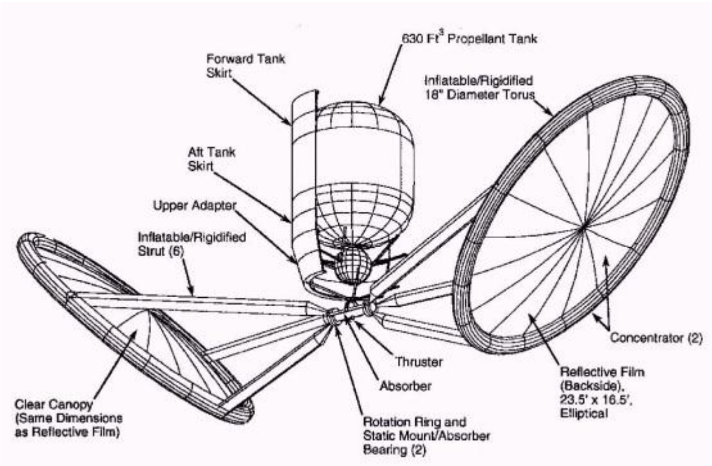
Solar energy drops to ~600W/m2 at Mars

Deployable large capture areas required

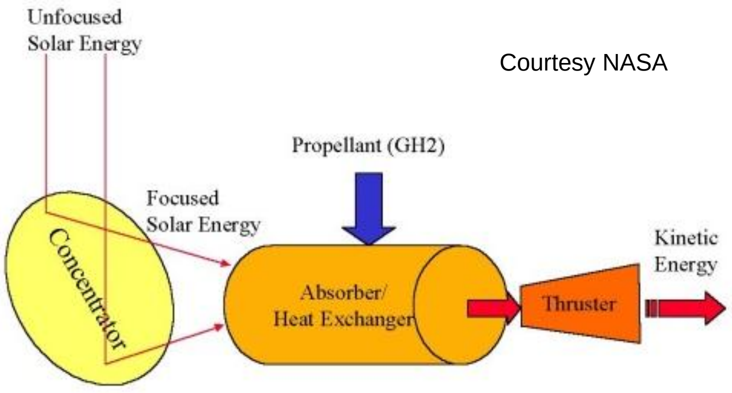


L'Garde Deployable Flight Experiment (14m Diameter)

Solar Thermal Propulsion



Courtesy NASA



Courtesy NASA

The STP system takes the unfocused solar energy impinging on a large collector/concentrator and transforms it into kinetic energy of a propellant for thrust from direct heating of the propellant or indirect heating via heat exchanger.

Thruster- Most thruster work in the past involved ground testing indirect solar heating as direct gain or thermal storage. Thrust range .5 – 2 lbs, Isp 700-860 seconds with hydrogen. Materials tested Tungsten, Tungsten/Rhenium alloys, Rhenium, Rhenium coated graphite. Experiments with carbides and carbide coatings. Temperature goal 2700-3000K. More testing needed to verify performance holds up to mission requirements.

Concentrator-Inflatable reflectors show the best promise made of polyimide CP to withstand space environment effects. Deployment of 4m x 6m off-axis parabolic inflatable reflector from storage package has been demonstrated. 50-60% efficiency.

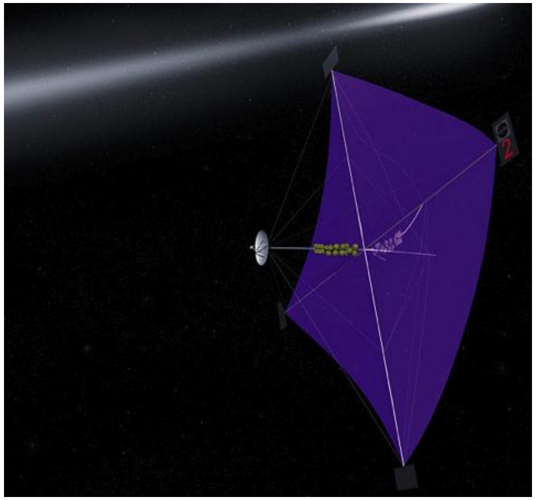
Propellant Utilization-Controlled 30 day boil-off of liquid hydrogen to pressure feed the thruster has been demonstrated.

SRS Inflatable Concentrator

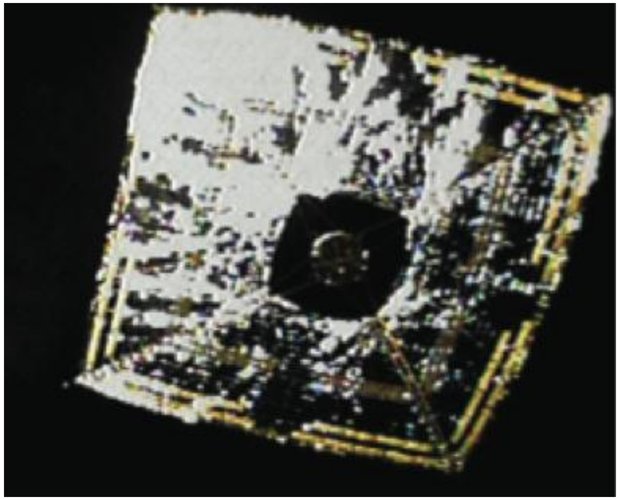
Direct Gain Thrusters

10kW solar Facility at MSFC

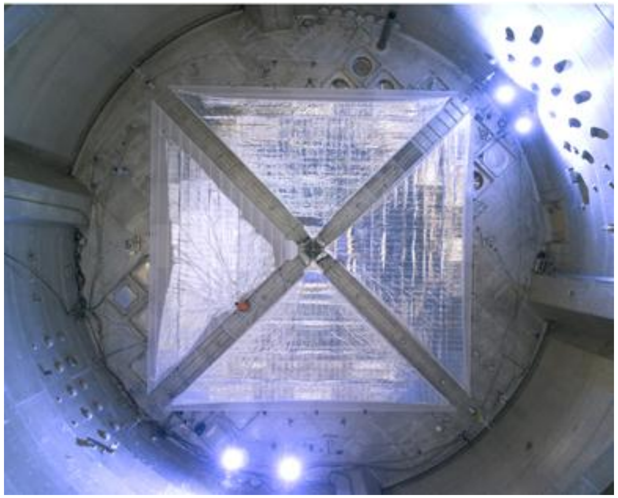
Propellantless-Solar Sails



NASA Concept Illustration



IKAROS Solar Sail after Deployment (IAC-10-A3.6.8)



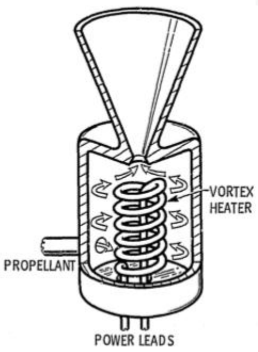
20 meter deployment test in NASA's Space Power Facility

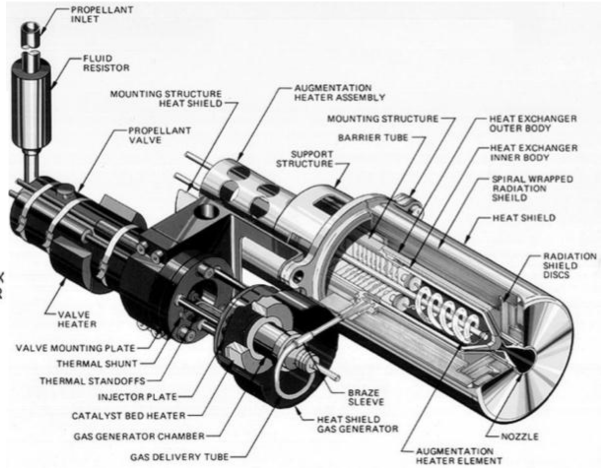
Solar sails are very large, very thin surfaces that reflect sunlight. The momentum transfer of the reflected photons generates thrust. The thrust vector is controlled by changing angle of the sail with respect to the sun. Sail material (aluminum coated Mylar, Kapton, or CP-1) is attached to long structural booms.

Electrothermal Thrusters

Resistojet

Typical





Typical Resistojet Design
(From: NASA-TM-83489)

Hydrazine Resistojet Schematic
(From: Jahn, R.G. and Choueiri, E.Y., "Electric Propulsion", Encyclopedia of Physical Science and Technology, 3rd Edition Volume 5, 2002.)

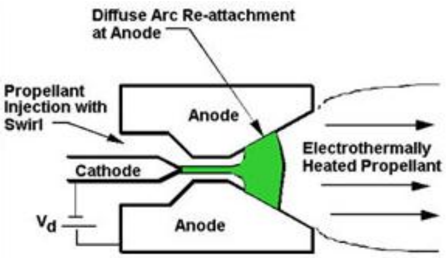
Propellant gas is passed over an electrically heated solid surface. This heats the gas, which then expands through a rocket nozzle.

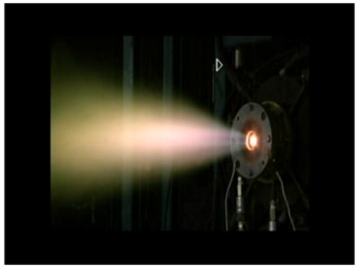
Aerojet MR-502A
Propellant: Hydrazine
Thrust: 800 – 360 mN
Isp: 303 – 294 s
Power: 885 – 610 W

SSTL Low-power Resistojet
Propellant: Xenon, Nitrogen, Butane
Thrust: up to 100 mN
Isp: 48 s (Xenon), 99 s (Nitrogen), 100 s (Butane)
Power: 15, 30, 50 W

Arcjet

Simple Schematic





MW Hydrogen Plasma Jet at MSFC

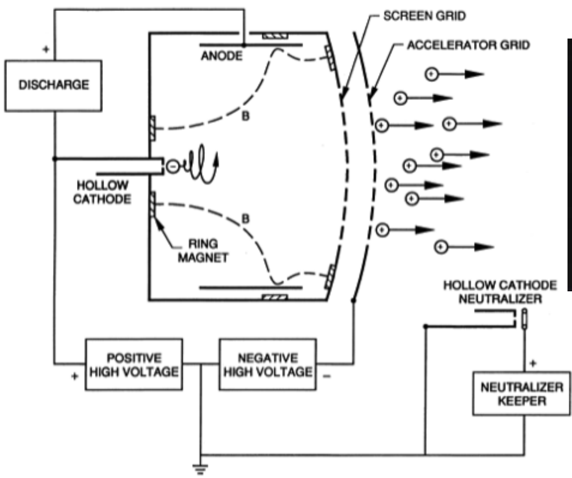
Propellant gas is heated by passing through a high-current electrical arc and then expands through a rocket nozzle.

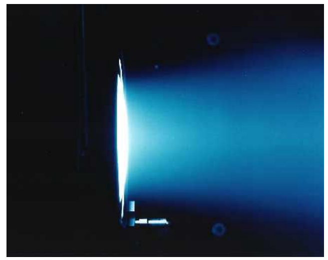
Aerojet MR-510 (off-the-shelf)
Propellant: Hydrazine
Thrust: 258 – 222 mN
Isp: 585 – 615 s
Mass: 1.58 kg
Power: 2 kW

Electrostatic Thrusters

Ion Thrusters

Typical Engine Schematic

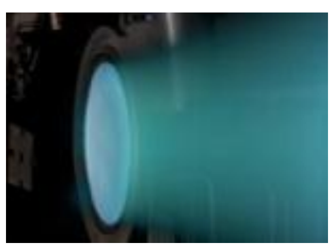




General Ion Thruster Schematic
("Electric Propulsion", Jahn and Choueiri)

Propellant gas is ionized in a discharge chamber. Resulting ions are electrostatically accelerated through two or more grids. Ion beam is typically neutralized by electrons emitted from external cathode.

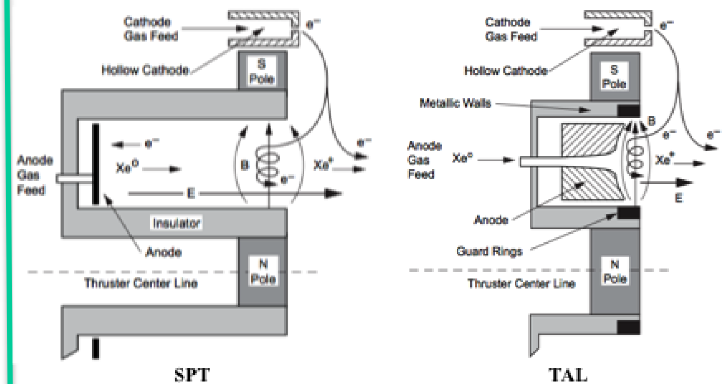
NEXT
Propellant: Xenon
Grid diameter: 40 cm
Thrust: 26 - 236 mN
Isp: 1410 - 4190 s
Mass: 12.7 kg (13.5 kg with cable harness)
Thruster input power: 0.5 – 6.9 kW

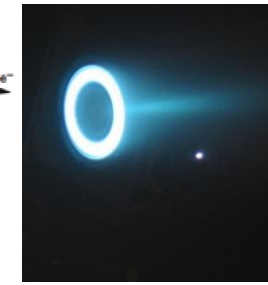


NEXT in Operation
(IEPC-2011-161)

Hall Thrusters

Typical Engine Schematics





General Hall Thruster Schematics
("Fundamentals of Electric Propulsion: Ion and Hall Thrusters", Goebel and Katz)

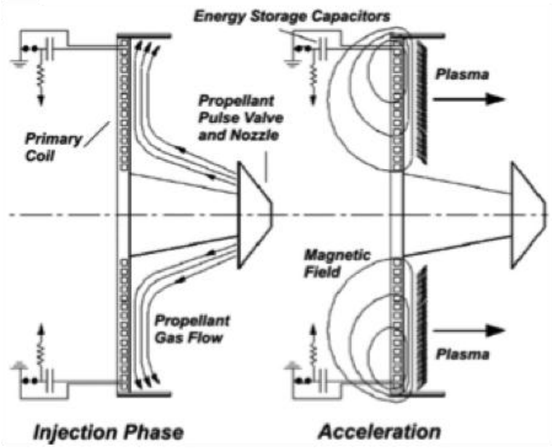
Electrons emitted from external cathode travel toward anode. Strong axial electric and radial magnetic fields near the thruster exit force the electrons into an azimuthal Hall current. Electrons also ionize the propellant, and these ions are accelerated through the electric field and are neutralized by electrons external to the thruster. There are two general types of Hall thrusters: SPT (ceramic discharge chamber, most popular) and TAL (shorter metallic chamber).

BPT-4000
Propellant: Xenon
Input power: 2.0 – 4.5 kW
Thrust: 117 - 290 mN
Isp: 1676 – 2020 s
Mass: < 12.3 kg

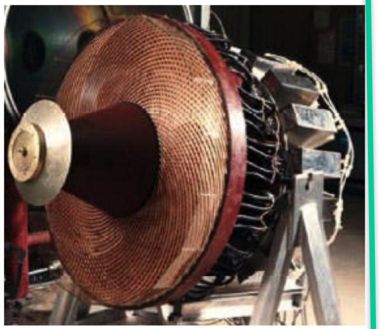
Aerojet BPT-4000

Electromagnetic Thrusters

Pulse Inductive Thrusters (PIT)



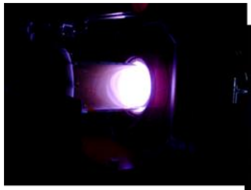
General PIT Thruster Operation
("Recent Advances in Nuclear Powered Electric Propulsion for Space Exploration", Cassady, et al.)



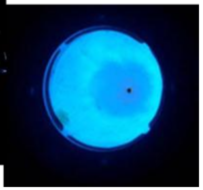
TRW Mark V PIT
(AIAA-2004-6054)

Propellant gas is injected against spiral induction coil. Strong current pulse is passed through coil, inducing transient magnetic field. This creates an electric field that ionizes the gas and also induces a current in the plasma. This azimuthal current interacts with the radial magnetic field (Lorentz force) to accelerate the plasma in the axial direction.

Mark Va PIT
Propellant: ammonia, argon, carbon-dioxide
Isp: 4000 – 8000 s (ammonia)
Efficiency: ~ 45 – 55% (ammonia)
Impulse per pulse: 0.15 – 0.05 N·s

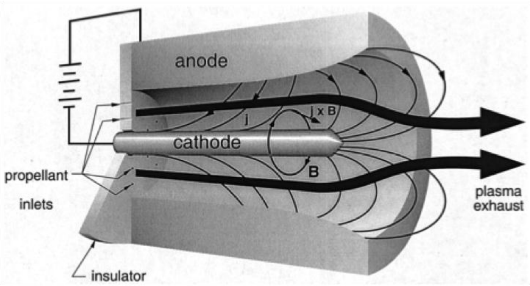


Field Reverse Configuration

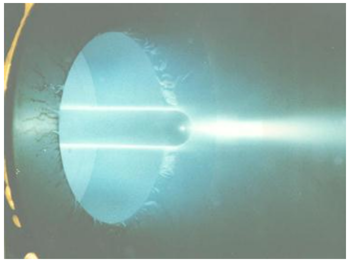


Conical Theta Pinch

Magnetoplasmadynamic (MPD)

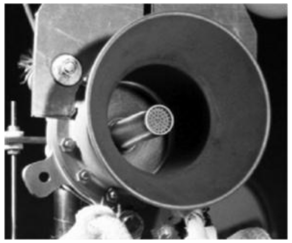


MPD Schematic
(Encyclopedia.pdf, Jahn, Choueiri)



Magnetoplasmadynamic (MPD) thrusters are coaxial devices with central cathode surrounded by annular anode, separated by an interelectrode insulator. Gaseous propellant is fed into the channel and is ionized by a uniform electric arc between the electrodes. The current through the plasma induces an azimuthal magnetic field. In a self-field MPD (SF-MPD), the interaction between the current and magnetic field (Lorentz force) is utilized to accelerate the plasma from the engine. In an applied field MPD (AF-MPD), external coils provide an additional magnetic field to increase thruster performance.

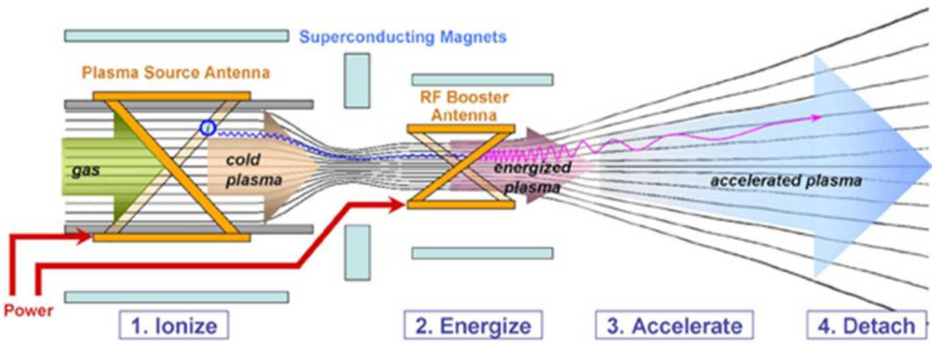
MAI 200kW
Propellant: Lithium
Thrust: 12.5 N
Isp: 4240 s
Efficiency: 50%
Input power: 200 kW
Lifetime: > 500 hr



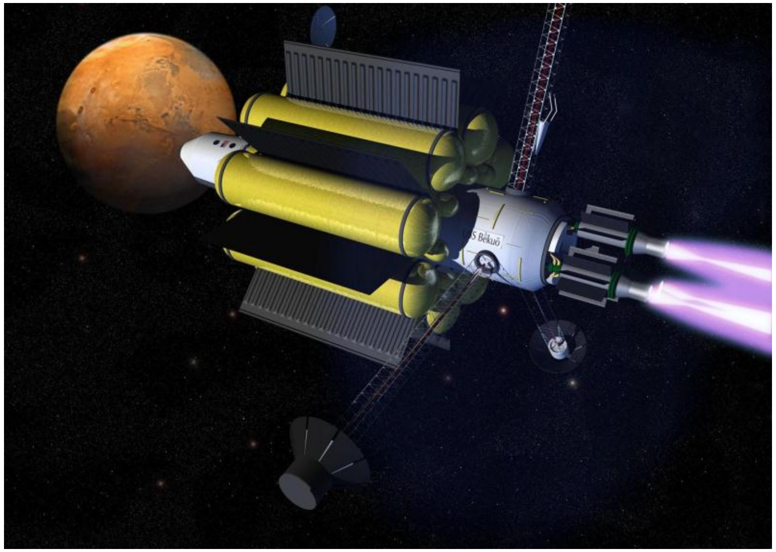
100 kW, Lithium AF-MPD

Electromagnetic Thrusters (Cont'd)

VASIMR (Variable Specific Impulse Magneto-plasma Rocket)



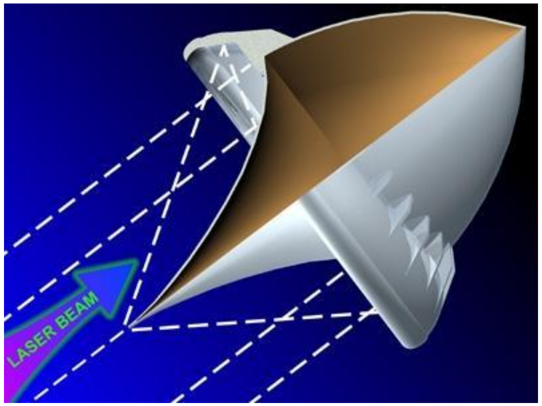
VASIMR Operation Schematic
(http://www.adastrarocket.com/aarc/Technology)



High power, electrode-less concept designed to operate at high power levels (hundreds of kilowatts to megawatts). Propellant gas is ionized by helicon antenna. Plasma is heated to very high temperature by ICH RF antenna. Magnetic nozzle converts transversal plasma motion to axial, creating thrust.

VX-200 (Ad Astra Rocket Company)
Propellant: Argon
Thrust: 5.7 N
Isp: 5000 s
Efficiency: 72%
Input power: 200 kW

Laser Propulsion-Lightcraft



10kW pulse laser tests at WSTF

Leik Myrabo's "lightcraft" design is a reflective funnel-shaped craft that channels heat from the laser, towards the center, causing it to literally explode the air underneath it, generating lift. This method, however is dependent entirely on the laser's power, and even the most powerful models currently can only serve for modest test purposes. To keep the craft stable, a small jet of pressurized nitrogen spins the craft at 6,000 revolutions per minute. Lightcraft were limited to paper studies until about 1996, when Myrabo and Air Force scientist Franklin Mead began trying them out.

The first tests succeeded in reaching over 100 feet, which compares to Robert Goddard's first test flight of his rocket design.

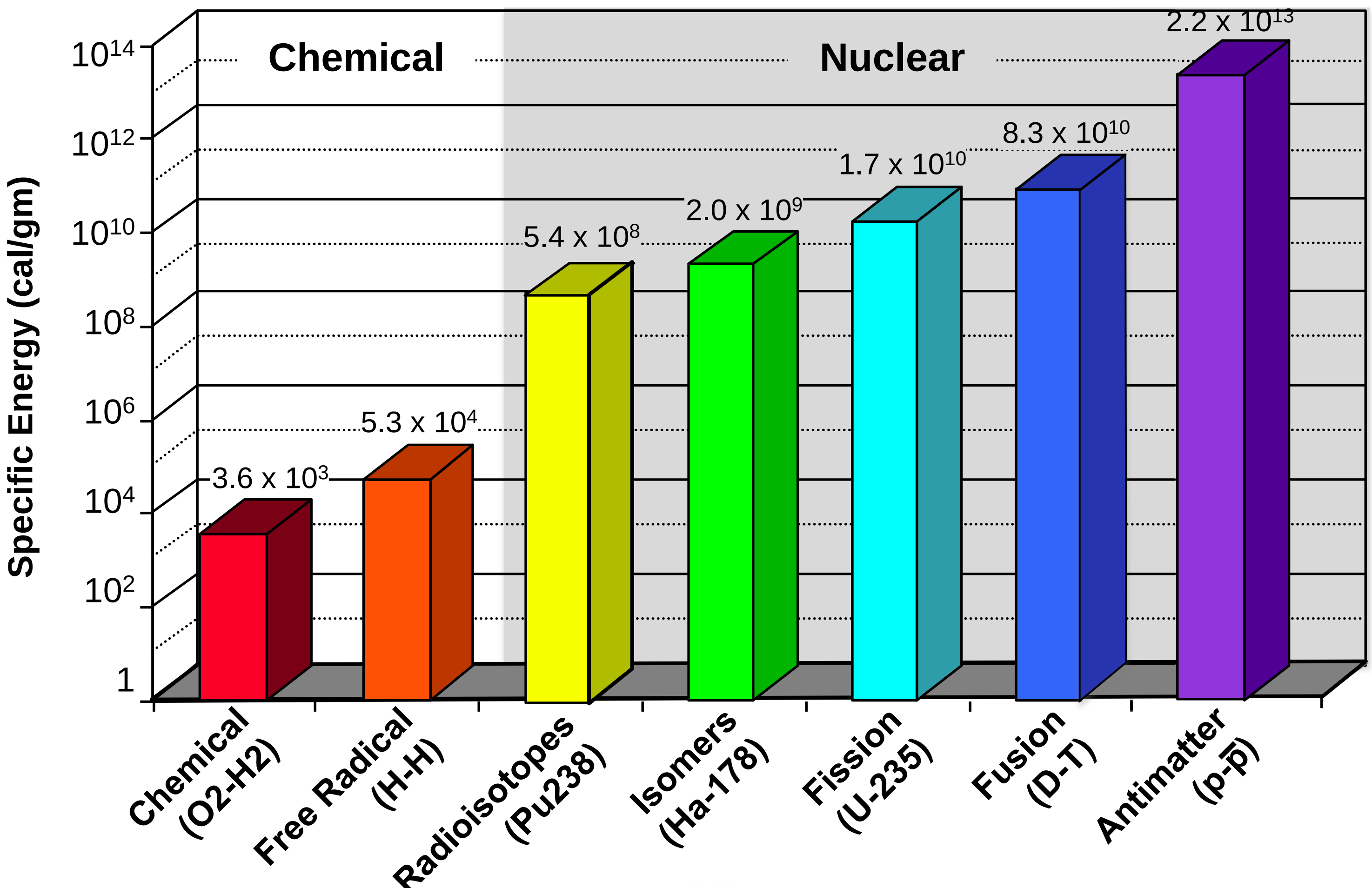
“…the navigation of interplanetary space depends for its solution on the problem of atomic disintegration…”

Robert H. Goddard, Father of American Rocketry

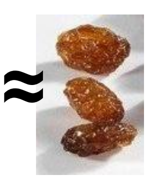
Robert H. Goddard, 1907

Why Nuclear?

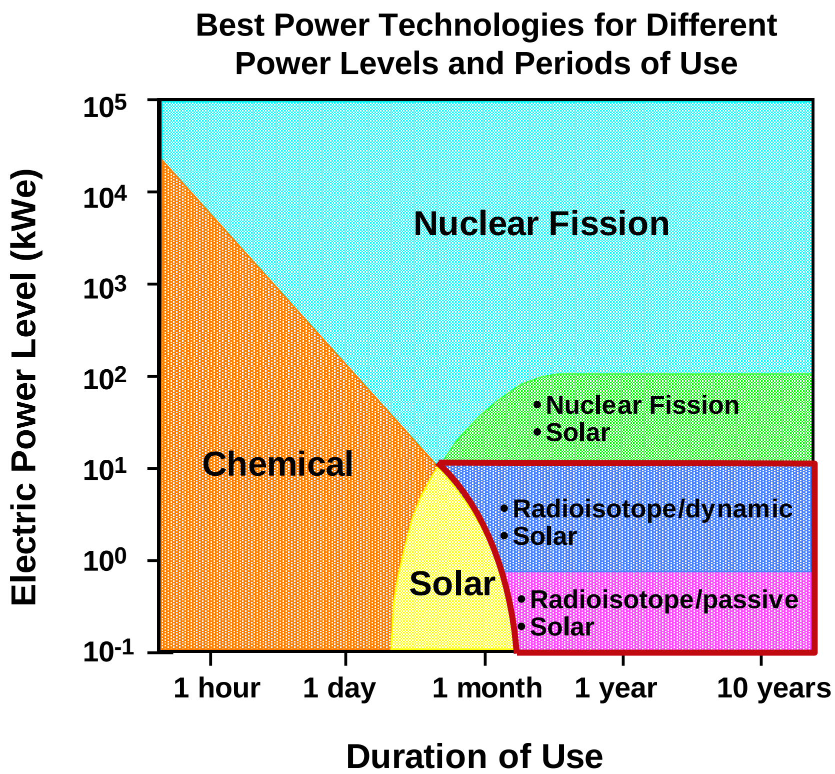
Specific Energy for Different Reactions



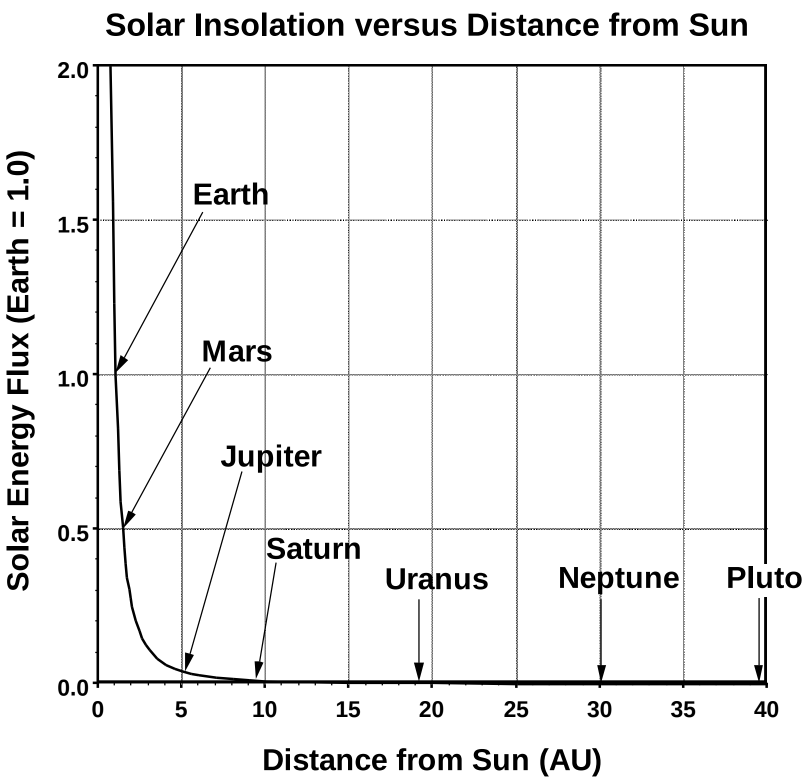
50 x  Chemical energy in Shuttle External Tank ≈ 

Energy in 12 fl oz (355 ml) of Uranium-235
(assumes total consumption) ≈  Energy in 3 gm (~3 raisins) of antimatter
(assumes total consumption)

Why Nuclear?



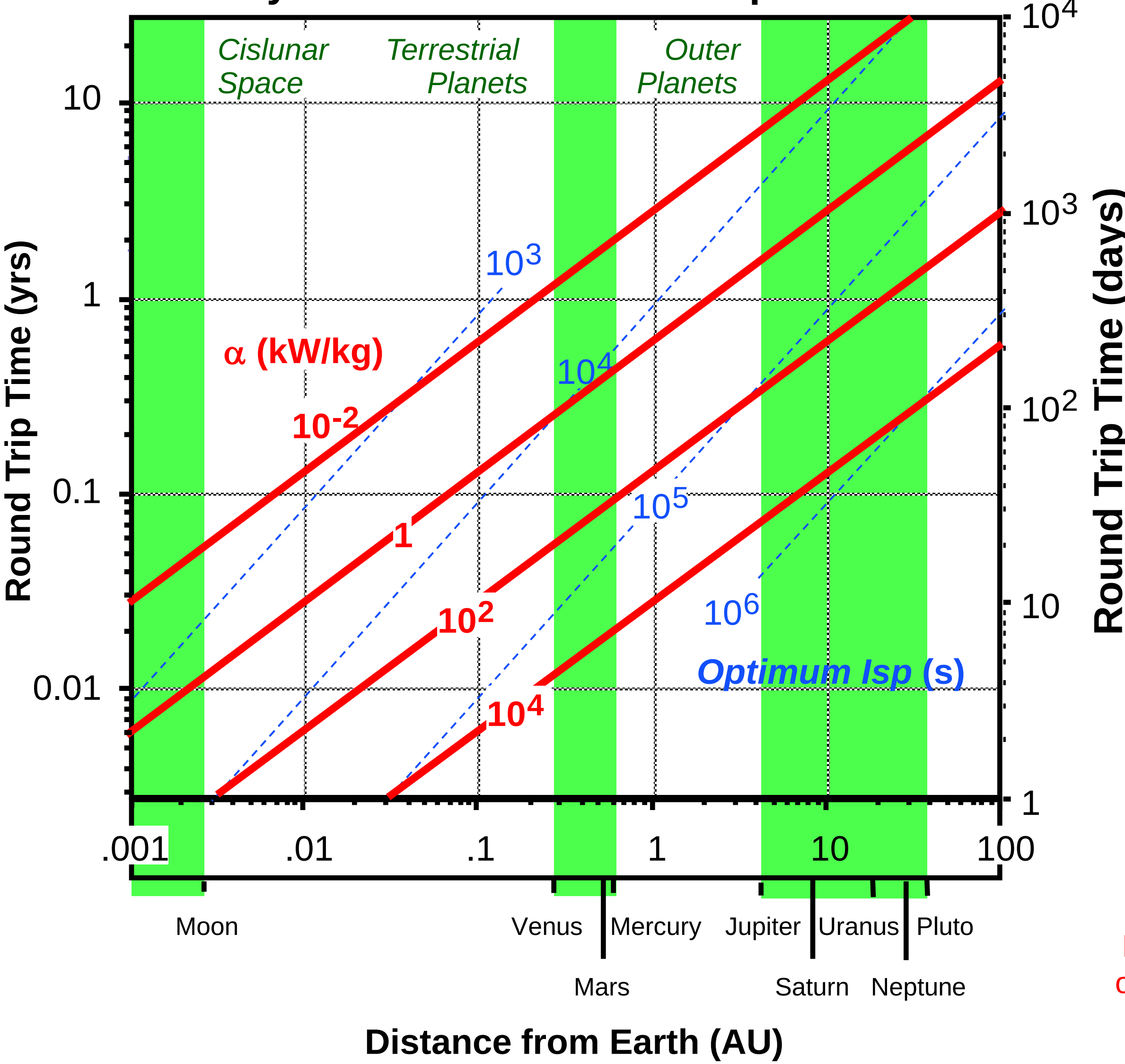
- **Vast amount of energy available for missions of long duration**
- **Continuous power independent of distance and orientation with respect to Sun**



- **Ideal for applications in…**
  - Deep space
  - Shadowed surface regions
  - Thick planetary atmospheres, including extreme environments (e.g., Venus, Titan)
  - High-radiation environments (e.g., Jovian system)

Ambitious Exploration Demands High Specific Power (α) and High Specific Impulse (Isp)

Round Trip Time to Destinations in the Solar System as a Function of Isp and α



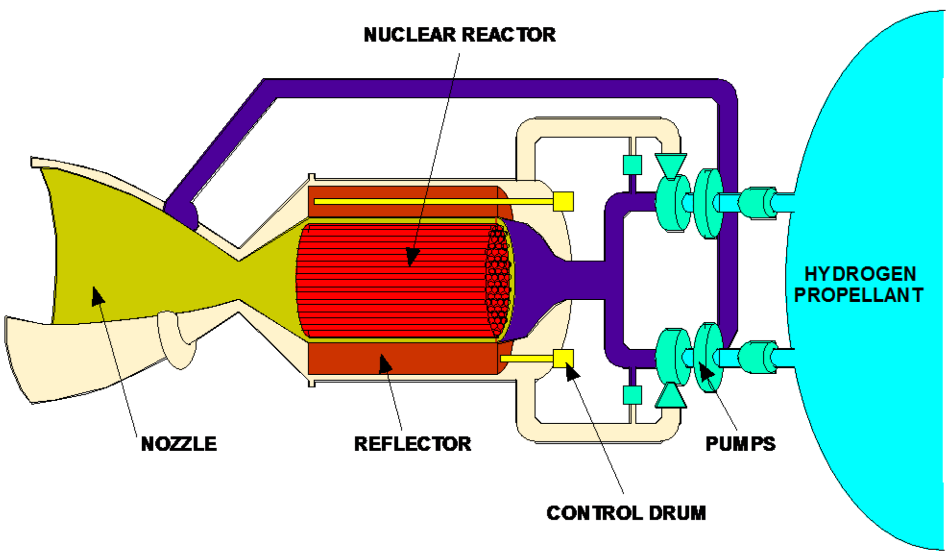
Nuclear Electric Propulsion (NEP) needs an α close to 1!

System	α (kW/kg)
JIMO – SOA Nuclear Electric Prop (NEP)	~0.01
Multi-MW NEP	~0.03
FAST-based SEP (Earth – Mars)	~0.1
VASIMR and other Plasma Systems (~100 day Round Trip to Mars)	≥1.0

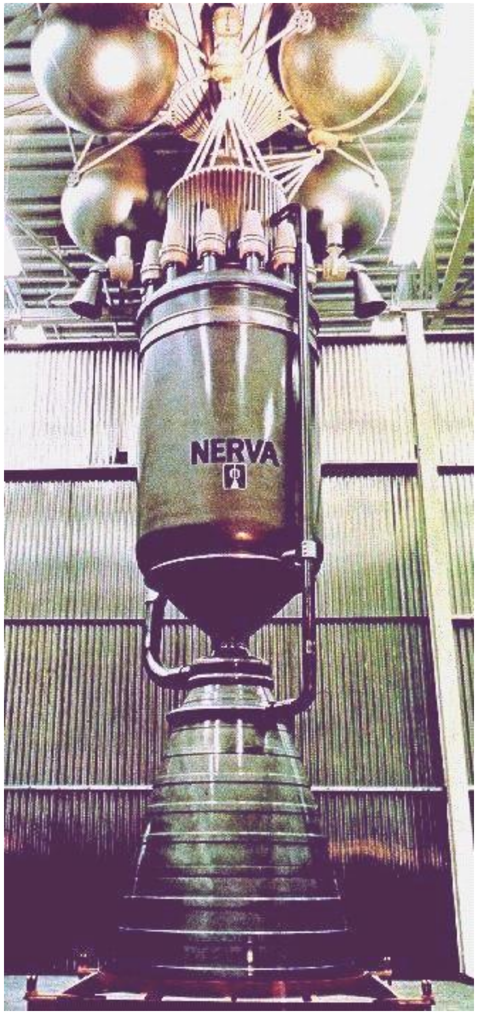
Requires ≥2 Order of Magnitude increase over JIMO-class nuclear power systems – a very ambitious goal!

Nuclear Thermal Propulsion (NTP)

- Propellant heated directly by a nuclear reactor and thermally expanded/accelerated through a nozzle
- Low molecular weight propellant – typically Hydrogen
- Thrust directly related to thermal power of reactor: 50,000 N ≈ 225 MW_{th} at 900 sec
- Specific Impulse directly related to exhaust temperature: 830 - 1000 sec (2300 - 3100K)
- Specific Impulse improvement over chemical rockets due to lower molecular weight of propellant (exhaust stream of O2/H2 engine runs hotter than NTP)



Major Elements of a Nuclear Thermal Rocket



Nuclear Thermal Rocket Prototype

Rover/NERVA Nuclear Rocket Program

NTP Reactors Tested in the Rover Nuclear Rocket Program

KIWI A
1958-1960
100 MW
0 lbf Thrust

KIWI B
1961-1964
1,000 MW
50,000 lbf Thrust

Phoebus 1
1965-1966
1,000 & 1,500 MW
50,000 lbf Thrust

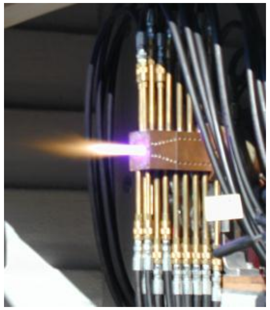
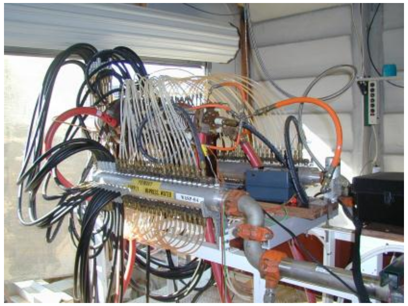
Phoebus 2
1967
5,000 MW
250,000 lbf Thrust

NERVA engines based largely on the KIWI B reactor design.

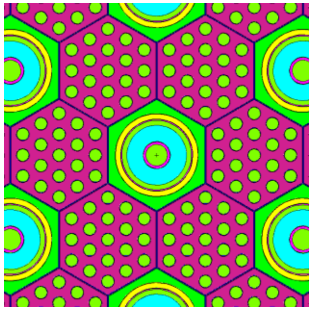
Culmination of NERVA Program

XE-Prime
1969
1,140 MW
55,400 lbf Thrust
28 engine restarts
115 minutes total run time
11 minutes at full power

Some Recent Activities in NTP

Hot-Hydrogen Materials Testing using 1-MW Arc-Heater

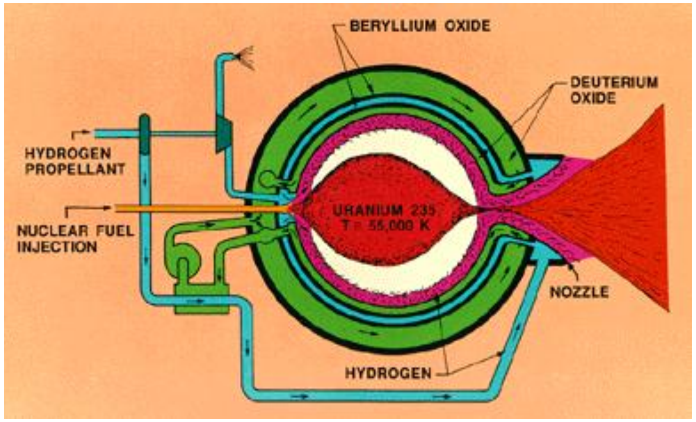



Architecture, Mission and System Analysis (e.g., DRA 5.0, HERRO-Mars, HERRO-Venus). Engine Modeling and Analysis.


Non-Nuclear Hot-Hydrogen Component Tester using Induction Heating to Simulate Fission (NTREES)

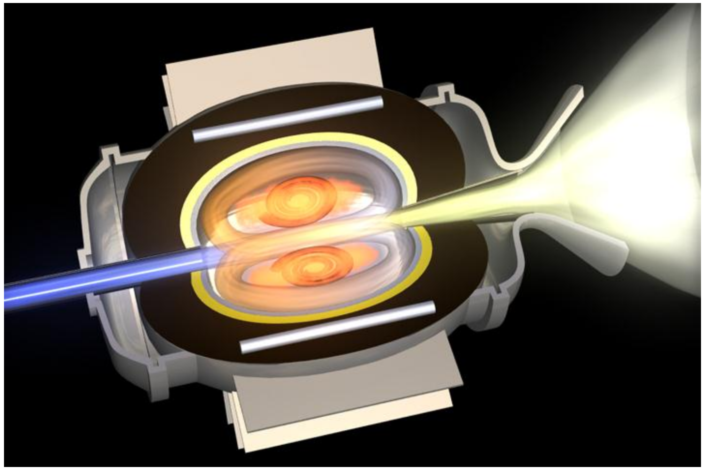
Evaluation of Environmentally Acceptable Ground Test Methods. Concept based on use of Bore Holes at Nevada Test Site

Gas Core Nuclear Thermal Rockets (GCNTR)

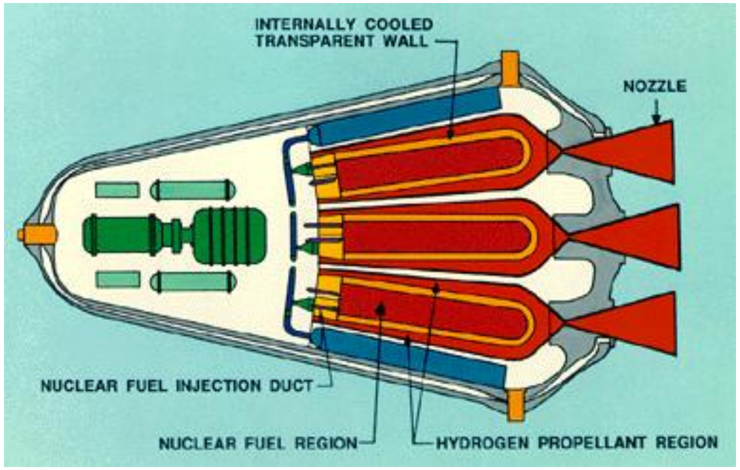


Early concept for open cycle GCTR

- Nuclear reactions take place in open or closed gaseous core. Enables operation at much higher temperatures than solid core rockets.
- Tests of "gaseous" fuel elements performed in 1975 and 1979. Equivalent Isp of 1350 secs demonstrated.
- CFD analyses periodically since then.
- Isp ≥ 2000 secs



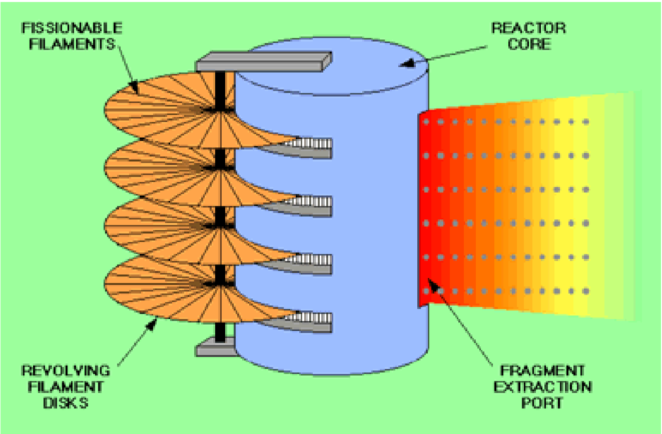
LANL (Howe) Vortex-stabilized GCTR from late-1990's to early-2000's



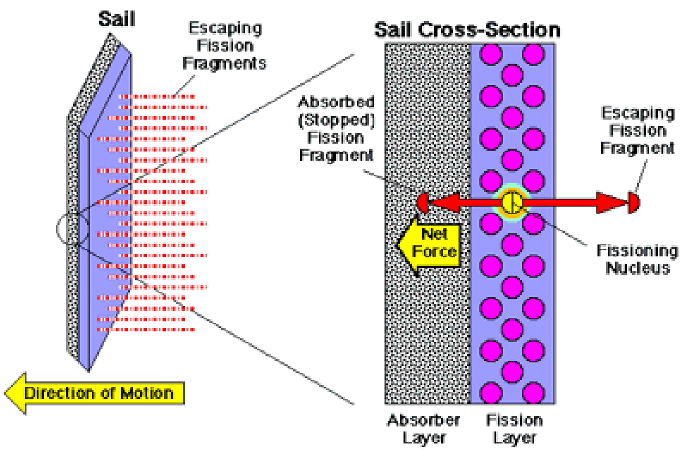
Closed cycle Nuclear Light Bulb Concept

Fission Fragment Rockets

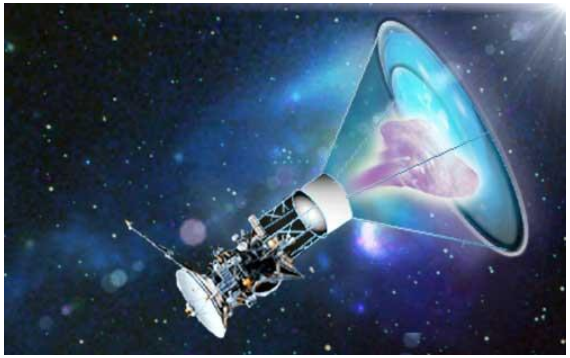
- Kinetic energy of fission fragments used directly to produce thrust
- Eliminates inefficiencies arising from thermalization in a core or other materials
- Most concepts based on highly-fissile isotopes, such as Americium-242
- Very high Isp of <100,000 sec appear to be possible



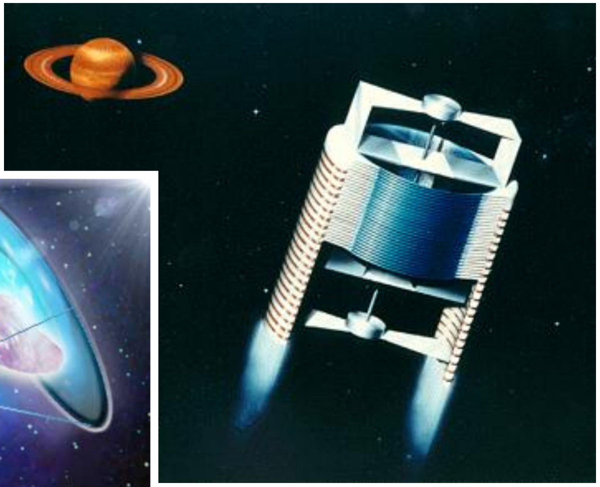
Rotating Filament Concept



Fission Sail Concept (R. Forward)

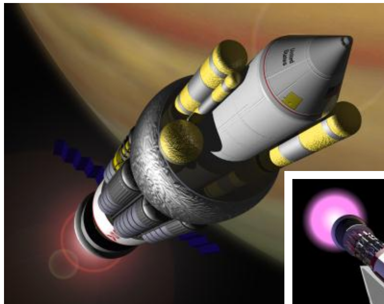


Antimatter-Facilitated Fission Sail (S. Howe)

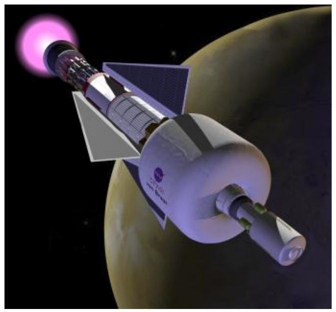


Directed Fragment Exhaust (Lawrence Livermore)

Nuclear Pulse Propulsion

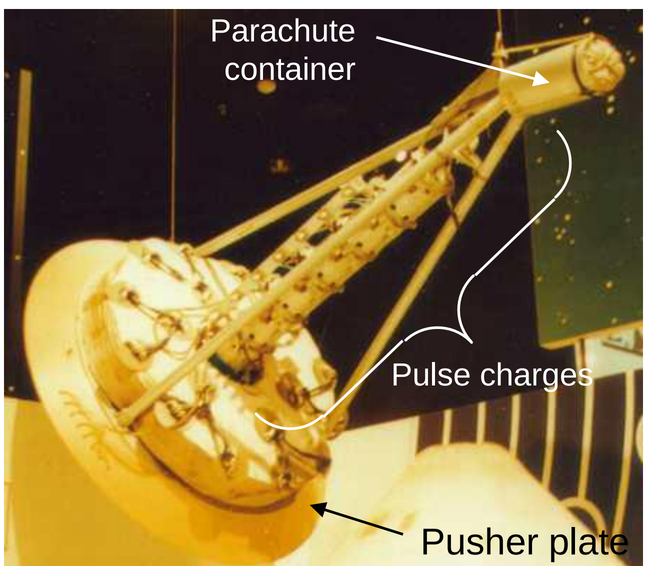


NASA Mars Mission Concept (1963-1965)



Modern All In-space Design

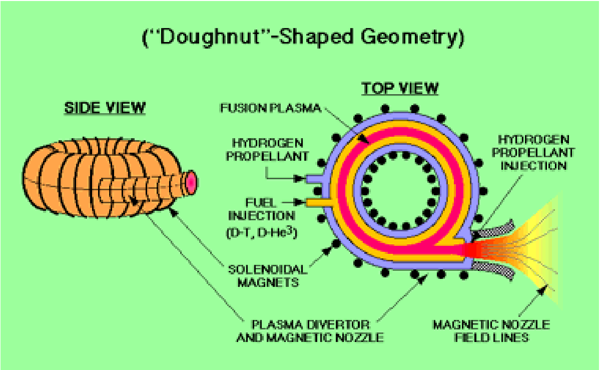
NPP Vehicle Concepts



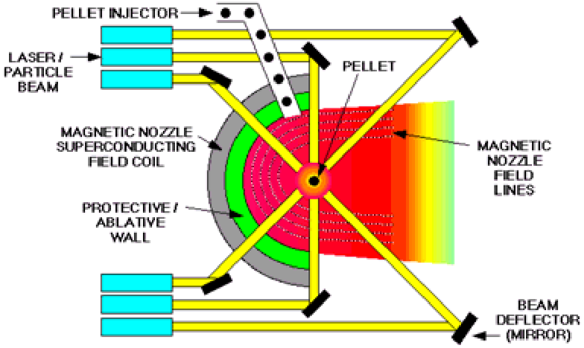
"Put-Put" Flight Test Vehicle on Display in Smithsonian Air & Space Museum

- Small nuclear energy release provide thrust via large pusher plate at rear of spacecraft
- First studied in 1950's and early 1960's for ARPA and then NASA as Project Orion
- Data from nuclear tests, analyses and subscale flights with chemical explosives pointed to feasibility for launch and in-space
- High Isp (~10,000 s) and high thrust (~1 g) attracted NASA interest as follow-on to Rover/NERVA technology
- More advanced politically-palatable versions have been studied since that could enable even higher performance
  - External compression/initiation using lasers, z-pinches, electron beams
  - Fusion and/or antimatter boosters/initiators

Fusion Propulsion

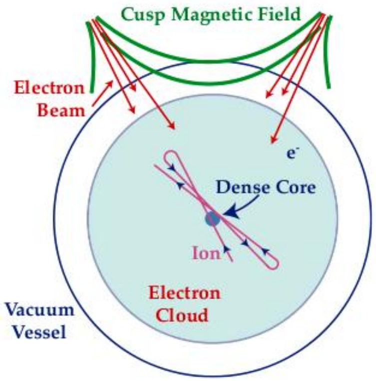


Magnetic Confinement Fusion



Inertial Confinement Fusion

Inertial Electrostatic Confinement Fusion



Magnetic Confinement

•Steady continuous energy production in a tokamak or magnetically confined plasma configuration
•Fusion research over last 50 years (TFTTR, ITER) indicates that this approach would be very large and massive
•Most recent studies by NASA GRC in 2005 suggest Isp of up to 45,000 s

Inertial Confinement

•Second main thrust of U.S. fusion research over last 60 years. Uses powerful lasers to implode fuel pellets and achieve high gain.
•National Ignition Facility (NIF) at Lawrence Livermore represents most recent research
•Studies suggest Isp's of 10,000 to 100,000 sec possible

Magnetized Target Fusion (MTF)

•New concept that was explored by Los Alamos and NASA Marshall in late-1990's and early 2000's
•Pulsed inertial compression of magnetized plasma targets. Could represent easier implosion technique and higher performance than classic inertial confinement
•Isp's of up to 70,000 sec appear possible

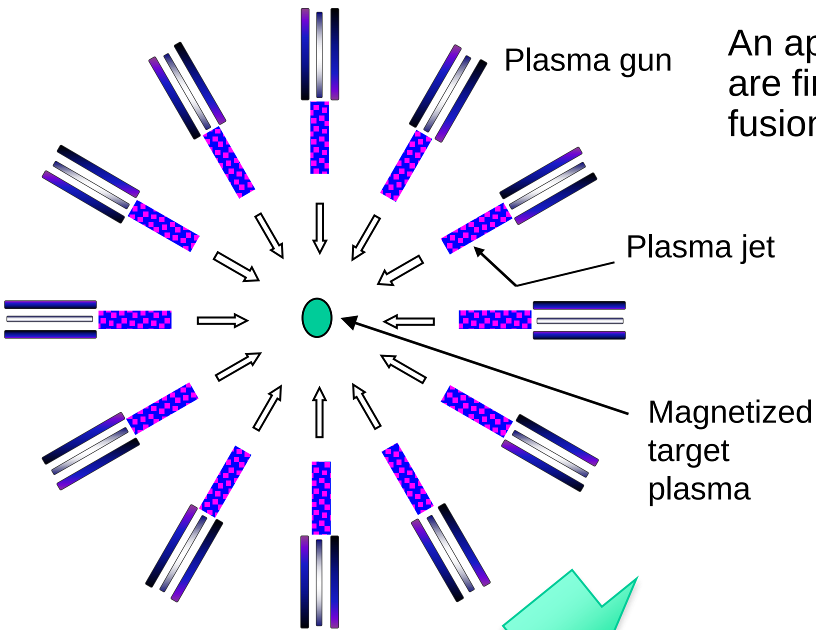
Inertial Electrostatic Confinement (IEC)

•Spherical chamber with radial electric field. Ions accelerated to center where they encounter high densities and temperatures.
•Pioneered by Philo Farnsworth (inventor of TV) and continued today by several universities and industry

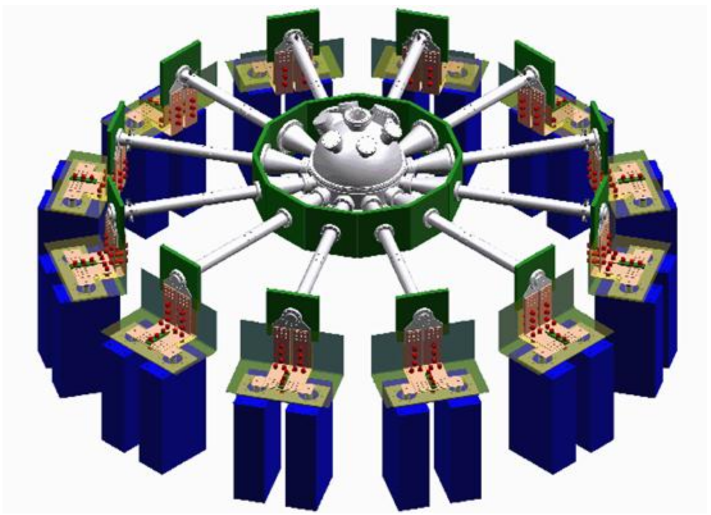
Antimatter-Catalyzed Fusion

•Conceived at Penn State, antiproton annihilation used to promote fusion.
•Most promising application for inertial confined techniques

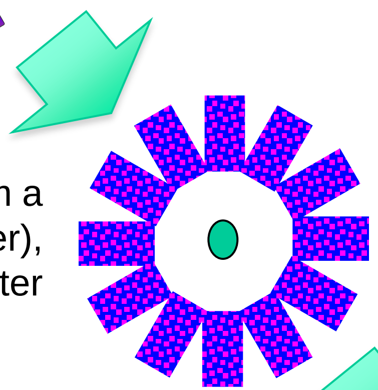
Magnetized Target Fusion (MTF)



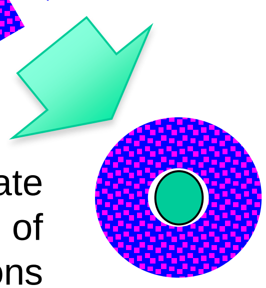
An approximately spherical array of jets are fired towards a magnetized toroid of fusionable plasma (at ~200 km/s)

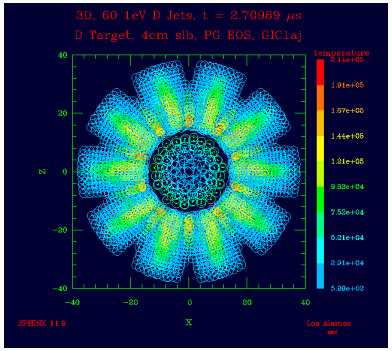


Test chamber design



The jets merge to form a spheroidal shell (liner), imploding towards the center

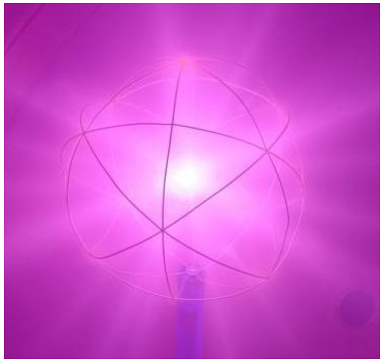




Modeling results

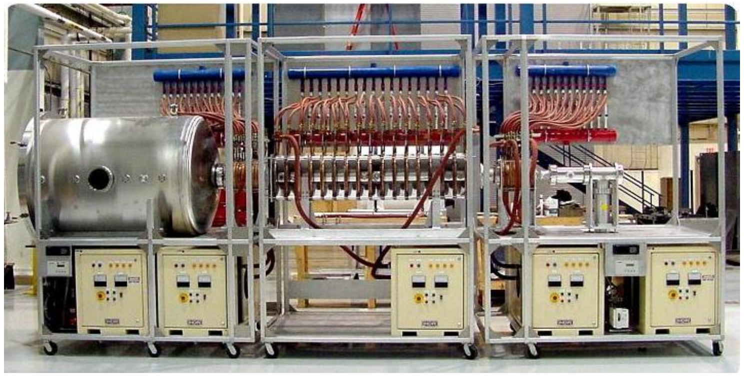
3-D hydrodynamics modeling results indicate plasma liner formation and compression of target plasma to fusion conditions

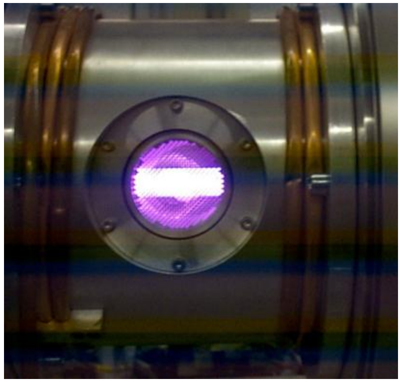
Fusion Propulsion Technologies Explored at MSFC

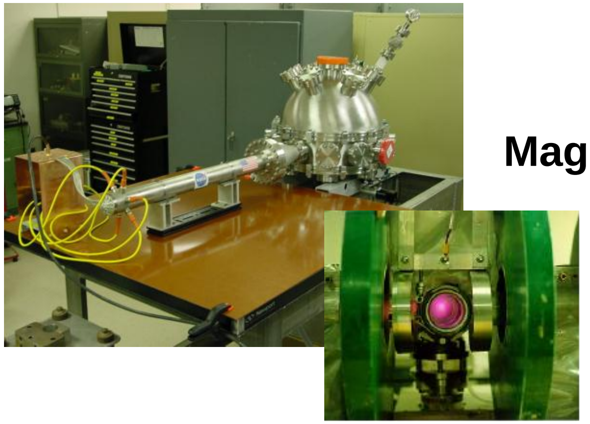


Inertial Electrostatic Confinement (IEC)

Gasdynamic Mirror (GDM)



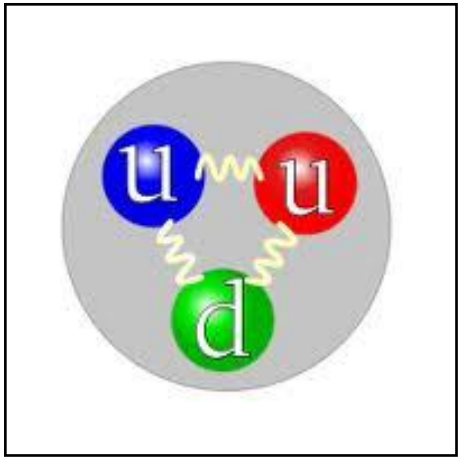


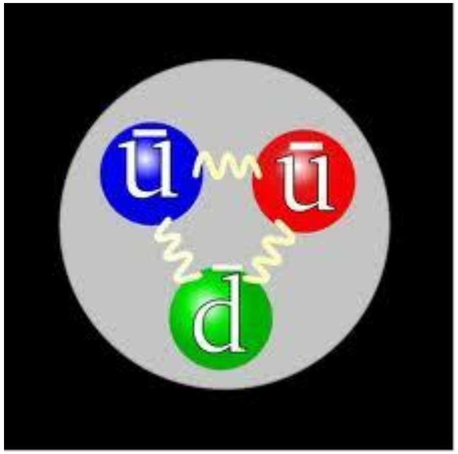


Magnetized Target Fusion (MTF)

Antimatter-Catalyzed Fission and/or Fusion

What is Antimatter?





Proton (positive charge) **Anti-Proton (negative charge)**

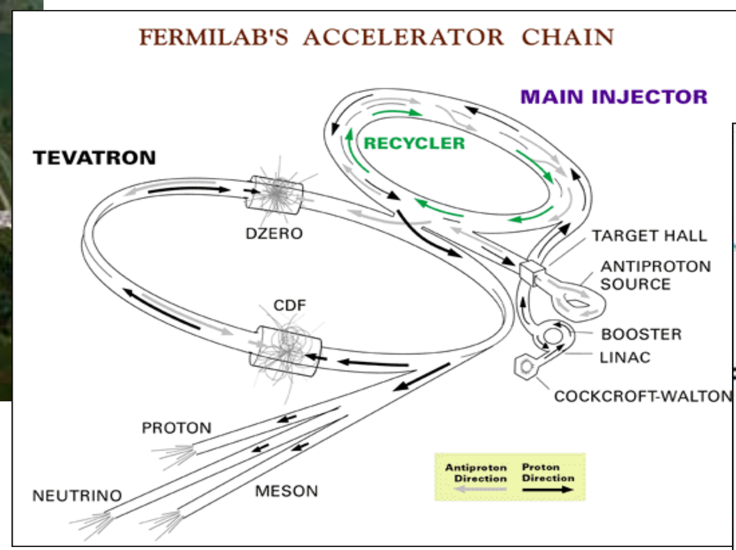
- Antimatter is composed of antiparticles (antiprotons, positron, antineutron)
- Antiparticles composed of smaller entities called quarks (or antiquarks for antimatter)
- Antiproton and positron have reversed charges and spin, but same rest mass
- Correlates with $E=mc^2$
- Matter and antimatter contact leads to annihilation cycle where most all rest mass decays to gamma rays

Where is Antimatter Produced?

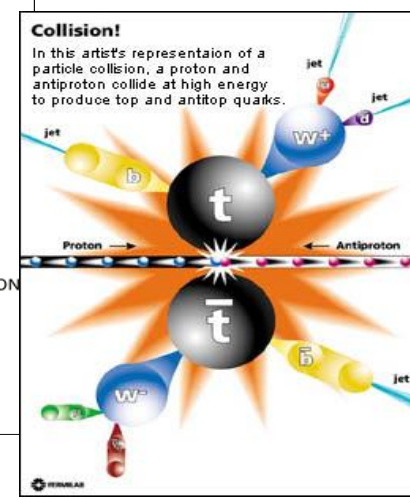
Antiprotons are routinely created to support high energy physics community.

- Fermi & Brookhaven National Accelerator Laboratories within the US ~10^{12} antiprotons per day
- Current systems are inefficient (limited user base). Cost ~ 64 B$/μg of antiprotons.

- World wide yearly antiproton (pbar) ~ 10 ng ($6x10^{15}$ pbars)
- FNAL production can be made 1000x more efficient.



Courtesy FNAL



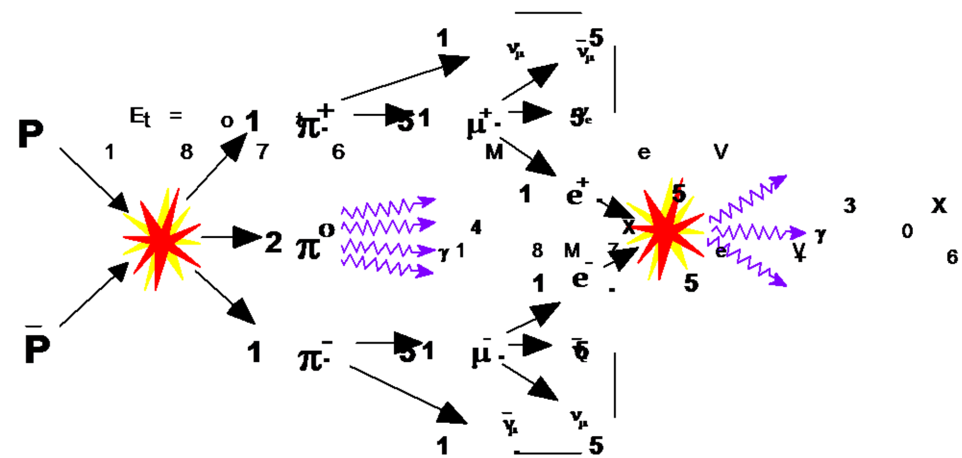
- **With near-term facility improvements ~$50 million, cost drops to $64 million/μg**
- **Milligram-scale facility would require ~ $10 billion investment, but could produce at $0.1 to $1 million/μg**

Courtesy Hbar Technologies LLC

Proton Antiproton Annihilation

Highest energy density of any reaction in known physics

- 1876 MeV per proton pbar annihilation
- 10 orders of magnitude greater than H_2/O_2 combustion.
- 1000 times greater than nuclear fission or fusion
- 100% conversion of mass to energy



On Average

$$\bar{p} + p \rightarrow m\pi^o + n\pi^+ + n\pi^-$$

where m and n are approximately 2.0 and 1.5, respectively

$$\pi^o \rightarrow \gamma + \gamma,$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu,$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

Charged pions have a range of ~21m
Gammas (γ) carry off ~40% of energy
Lifetime $\pi^o = 10^{-16}$ s, $\pi^{+/--} = 10^{-8}$ s

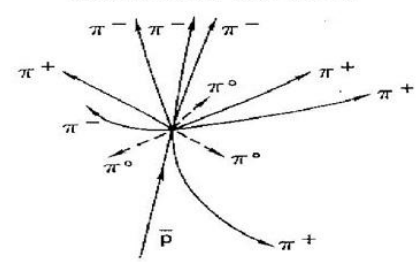
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu,$$
$$\mu^{-+} \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Muons have a range of ~1850m
Neutrinos (ν) carry off ~50% of energy
Lifetime $\mu = 10^{-6}$ s

$$e^+ + e^- \rightarrow \gamma + \gamma$$

Positron electron annihilation
Gamma (γ) carry off ~10% of energy

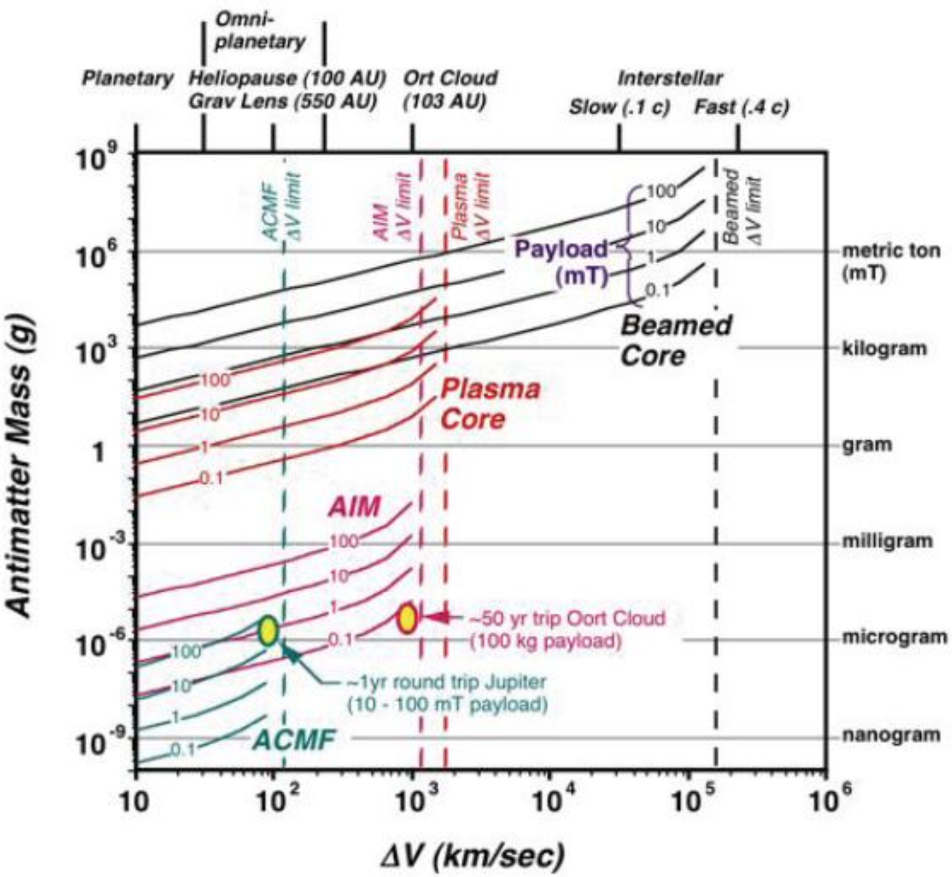
PROTON-ANTIPROTON ANNIHILATION



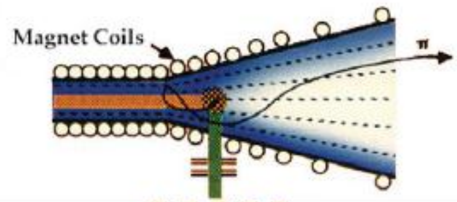
$p + \bar{p} \rightarrow m\pi^o + n\pi^+ + n\pi^-$

Antimatter Propulsion

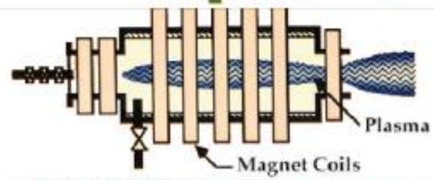
Antimatter Requirements for Various Missions and Propulsion Technologies



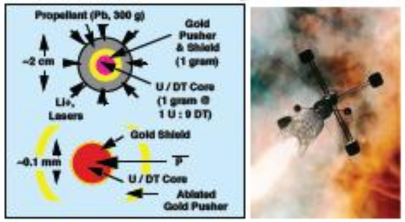
Antimatter-based Propulsion Technologies



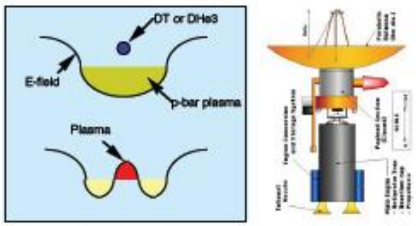
Beam Core
$Isp \approx 10^7$ s
$\eta_p \approx 60\%$
$\lambda \approx 0.2$



Plasma Core
$Isp \approx 10^5$ s
$\eta_p \approx 10\%$
$\lambda \approx 0.2$



Antimatter-Catalyzed Micro-Fusion (ACMF)
$Isp \approx 13{,}500$ s
$\eta_p \approx 15\%$
$\lambda \approx 0.7$
$\beta \approx 1.6 \times 10^7$

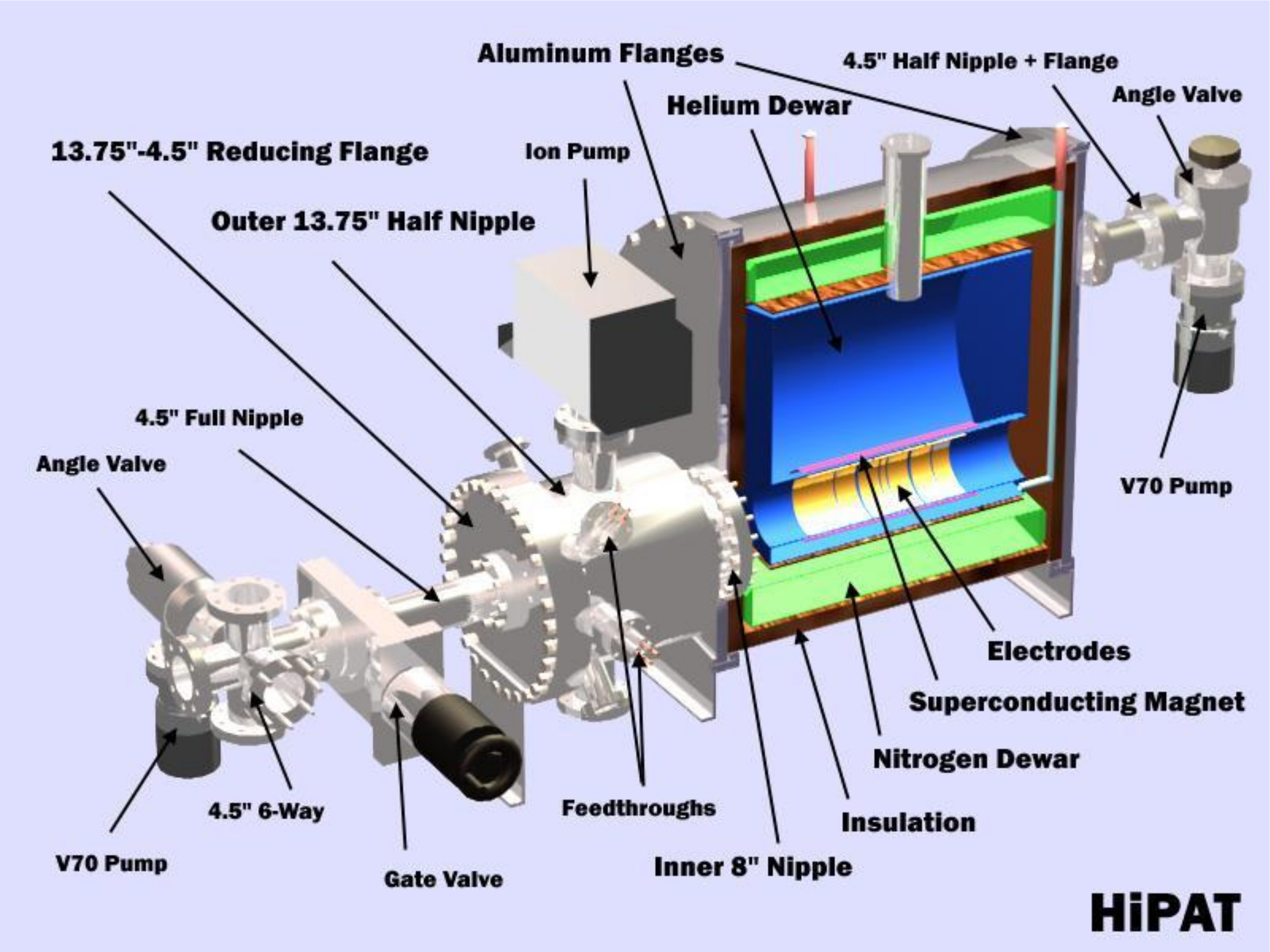


Antimatter-Initiated Micro-fusion (AIM)
$Isp \approx 67{,}000$ s
$\eta_p \approx 84\%$
$\lambda \approx 0.2$
$\beta \approx 10^5$

Isp Specific Impulse
η_p Propulsive energy utilization
λ Vehicle struct/prop mass ratio
β Fusion/annihilation energy ratio

- “Pure” antimatter propulsion not practical due to large antimatter requirement (≥ 1 gram). Current “cost” for 1 μg of p-bars is $63 million.
- With near-term improvements (x100 increase in efficiency) costs drop to $0.6 million/μg. This translates to antimatter costs of $0.6 million to $60 million for antimatter-assisted fission/fusion missions.

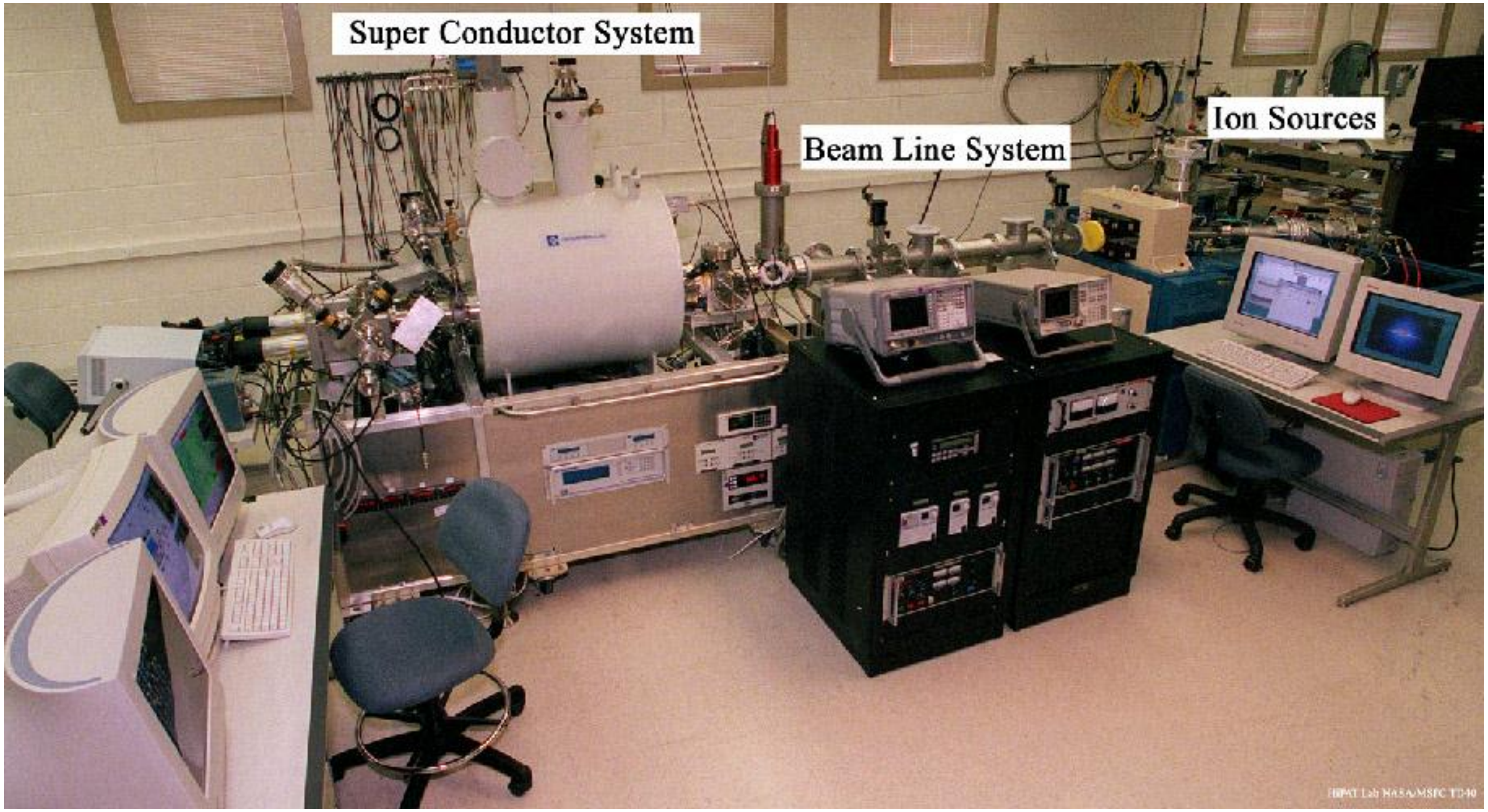
Hi Performance Antiproton Trap (HiPAT) at MSFC



HiPAT Laboratory

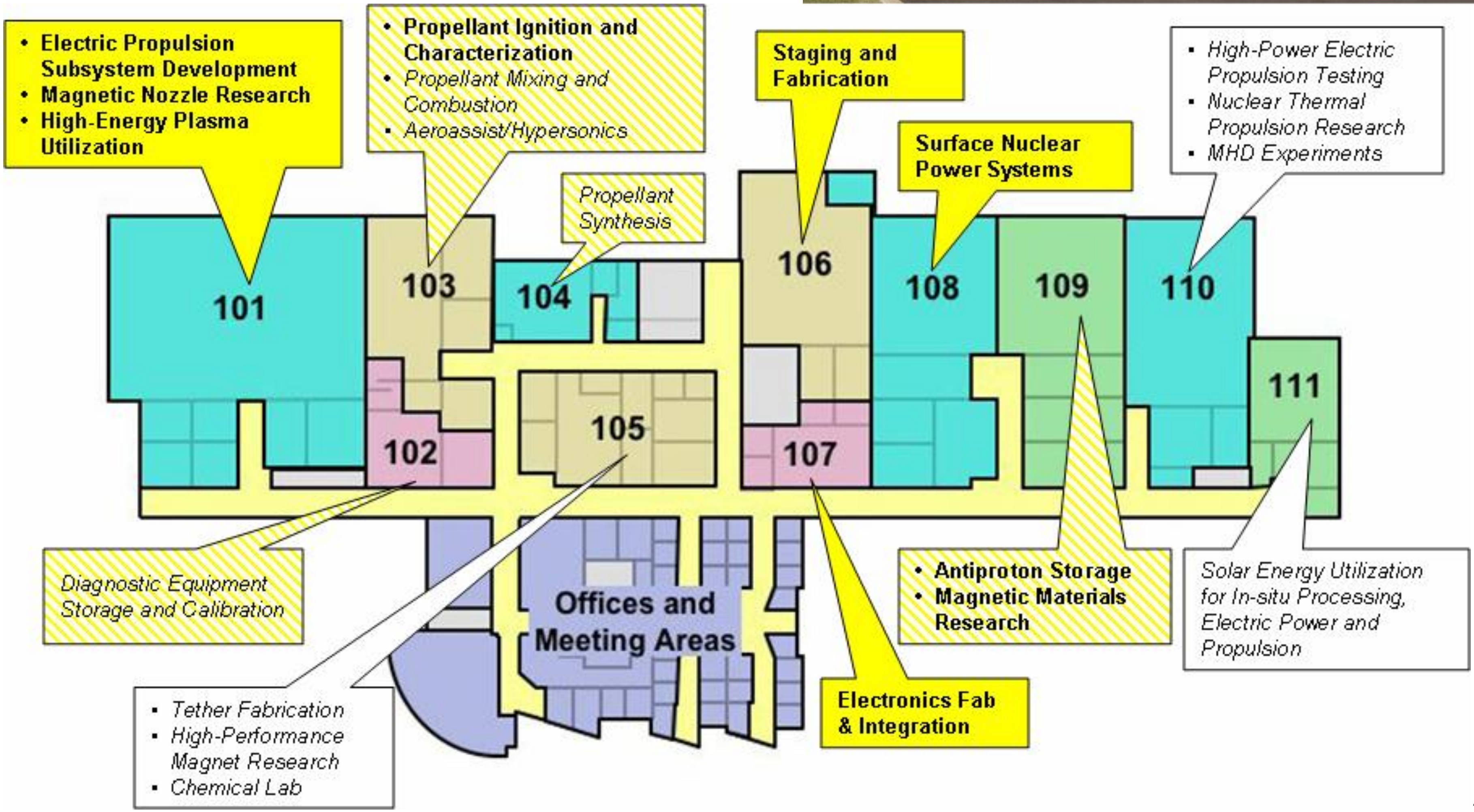
To address the storage issue, a test device termed the High Performance Antiproton Trap (HiPAT) has been designed and fabricated.

- Electromagnetic Penning-Malmberg design
- Capacity of up to 1×10^{12} antiprotons
- Storage lifetimes of 18 days or more
- Ultra high vacuum system ($<10^{-11}$ torr)
- Capable of portable operation
- RF stabilization and passive particle detection

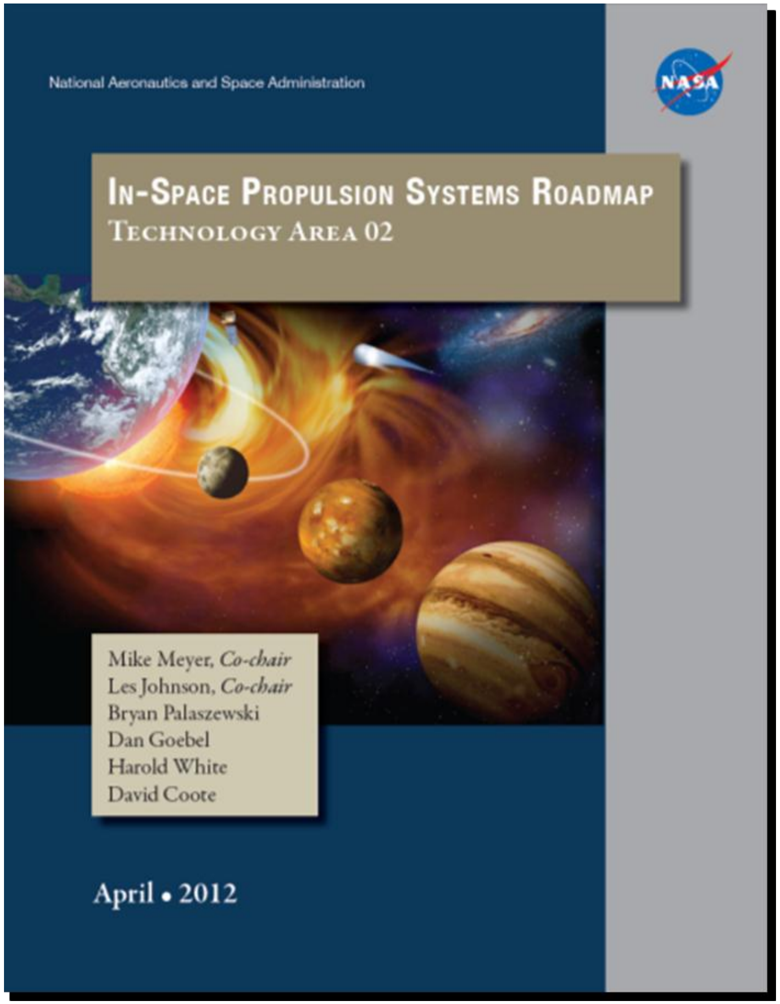


Special Facility Constructed for Advanced Propulsion

Original Propulsion Research Laboratory At Marshall Space Flight Center



In-Space Propulsion Technology Roadmap



Document summarizes the description, technical challenges and milestones for most in-space propulsion concepts

The National Research Council reviewed the roadmap and suggested the following in-space propulsion areas get high priority attention:

- **High Power Electric Propulsion Systems**
- **Cryogenic Storage and Transfer**
- **Nuclear Thermal Propulsion**
- **Micro-propulsion**

http://www.nasa.gov/pdf/501329main_TA02-ID_rev3-NRC-wTASR.pdf

Advanced Space Propulsion Workshop

NASA Jet Propulsion Laboratory (JPL)
NASA Marshall Space Flight Center (MSFC)
NASA Glenn Research Center (GRC)
U.S. Air Force Research Laboratory (AFRL)

19th Advanced Space Propulsion Workshop
November 27-29, 2012
U.S. Space & Rocket Center (USSRC)
Huntsville, Alabama

http://eis.jpl.nasa.gov/sec353/aspw2012/