Antimatter Propulsion

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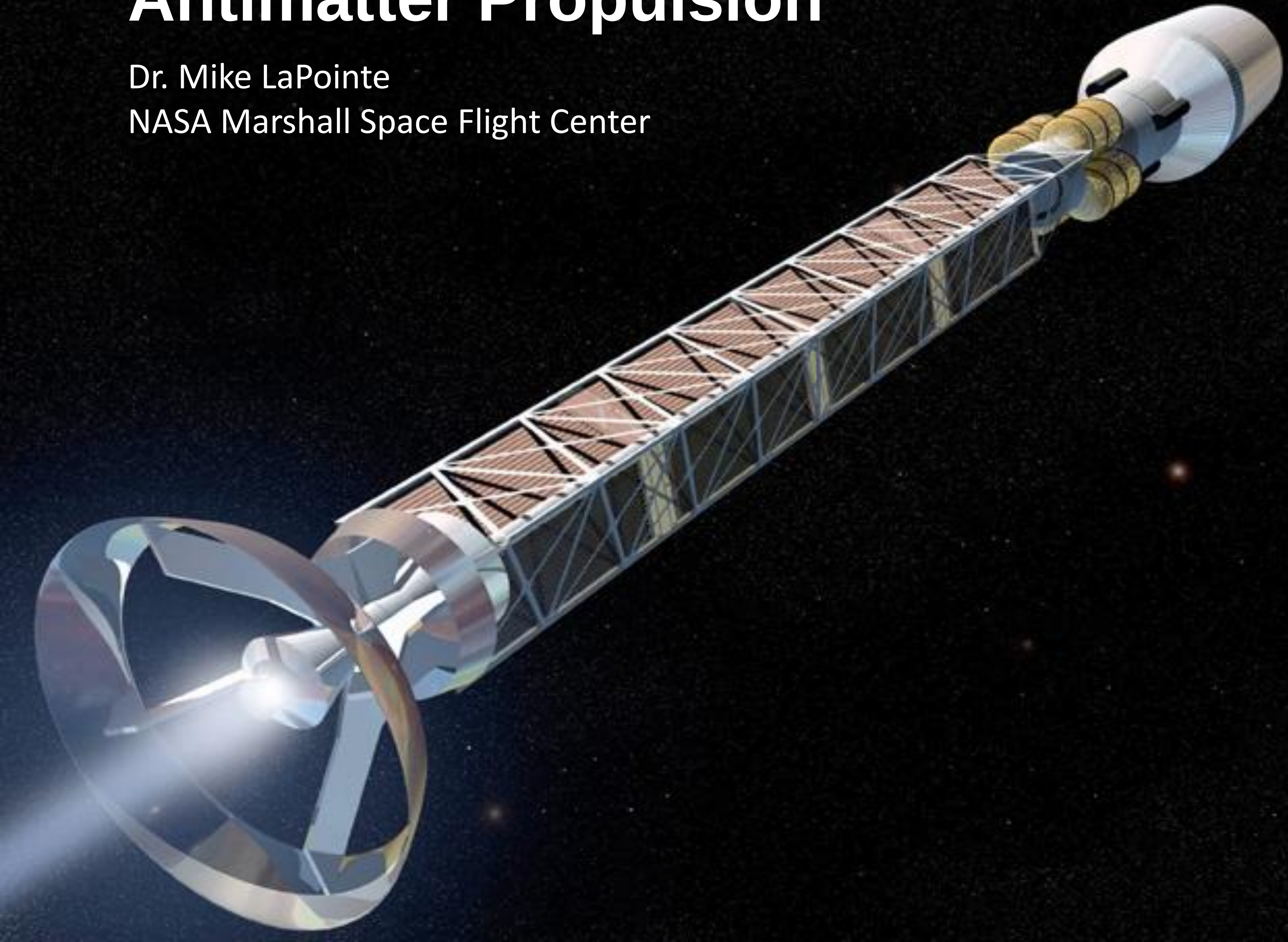


A Quick History

- **1928:** Dirac’s relativistic wave equation predicts the existence of antielectrons (positive electrons, or positrons)
- **1932:** Carl Anderson experimentally confirms the existence of positrons by studying the tracks of particles created by cosmic rays in a cloud chamber
- **1955:** Segrè, Chamberlain and colleagues confirm the existence of antiprotons using Berkley’s high energy Bevatron accelerator
- **Now:** Antimatter can be routinely (if expensively) created and stored at large high energy accelerators such as CERN, FNAL/FermiLab, and the Facility for Antiproton and Ion Research (FAIR; in development in Germany).

Interest for Propulsion

Energy!

- Fast trip times require high spacecraft velocities
- Higher spacecraft velocities require more kinetic energy
- High energy density propellants generate higher exhaust velocities and provide better payload fractions

$$\mathbf{\frac{M_f}{M_0} = e^{-\Delta V / V_e}}$$

M_0 = initial vehicle mass (total, including propellant)
M_f = final vehicle mass after propellant consumed
ΔV = Required velocity change for the mission
V_e = Propellant exhaust velocity

If $V_e \ll \Delta V$ then $M_f \ll M_0$ and most of the vehicle mass is propellant

Energy Density

Total energy released per unit mass:

Chemical combustion: ~ a few MJ/kg

- Solid Propellants: ~ 5 MJ/kg
- Liquid Propellants: ~ 1 MJ/kg

Nuclear Fission (U^{235}): ~ $8\text{x}10^7$ MJ/kg

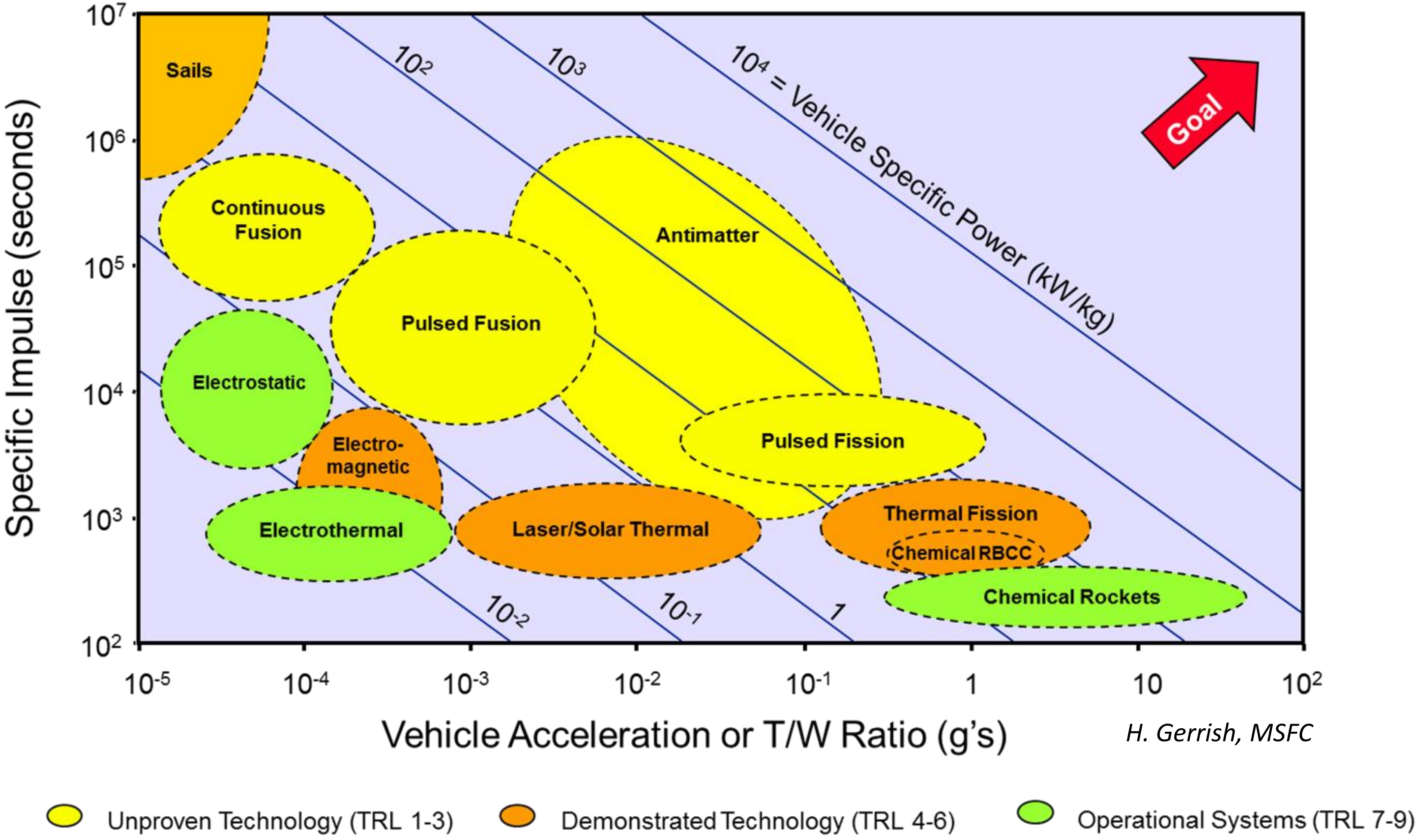
Nuclear Fusion (D-T): ~ $3.5\text{x}10^8$ MJ/kg

Antimatter: ~ $9\text{x}10^{10}$ MJ/kg (combined with matter)

- About 10 billion times more than chemical combustion
- About 1000 times more than nuclear fission
- About 300 times more than nuclear fusion

A lot of energy if we can use it efficiently!

Propulsion Landscape

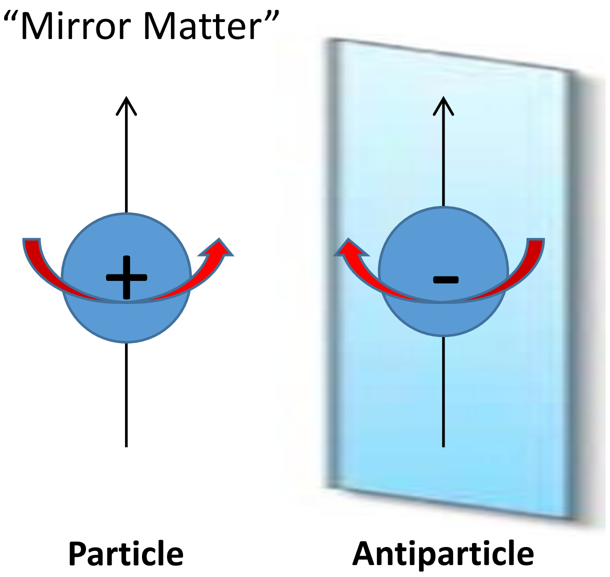


H. Gerrish, MSFC

What is Antimatter?

- **Compared to it’s matter counterpart, antimatter has:**
  - The same mass & lifetime
  - Opposite electrical charge
  - Opposite magnetic moment
- **Every particle has an antiparticle**

  (photons, π^0 and μ^0 mesons are their own antiparticles)
- **Anti-elements can be built up from antiparticles**
- **Antihydrogen ($\overline{\mathrm{H}}$):**
  - Positron (antielectron) orbiting an antiproton
  - Fleetingly created at the CERN accelerator in 1995
  - Stably created and studied by ATHENA/CERN in 2002
  - Neutral antihydrogen atoms briefly trapped by ALPHA/CERN in 2010
  - Antihydrogen atoms can now be routinely trapped for 1000’s seconds



Matter-Antimatter Reactions

Electron - Positron Annihilation

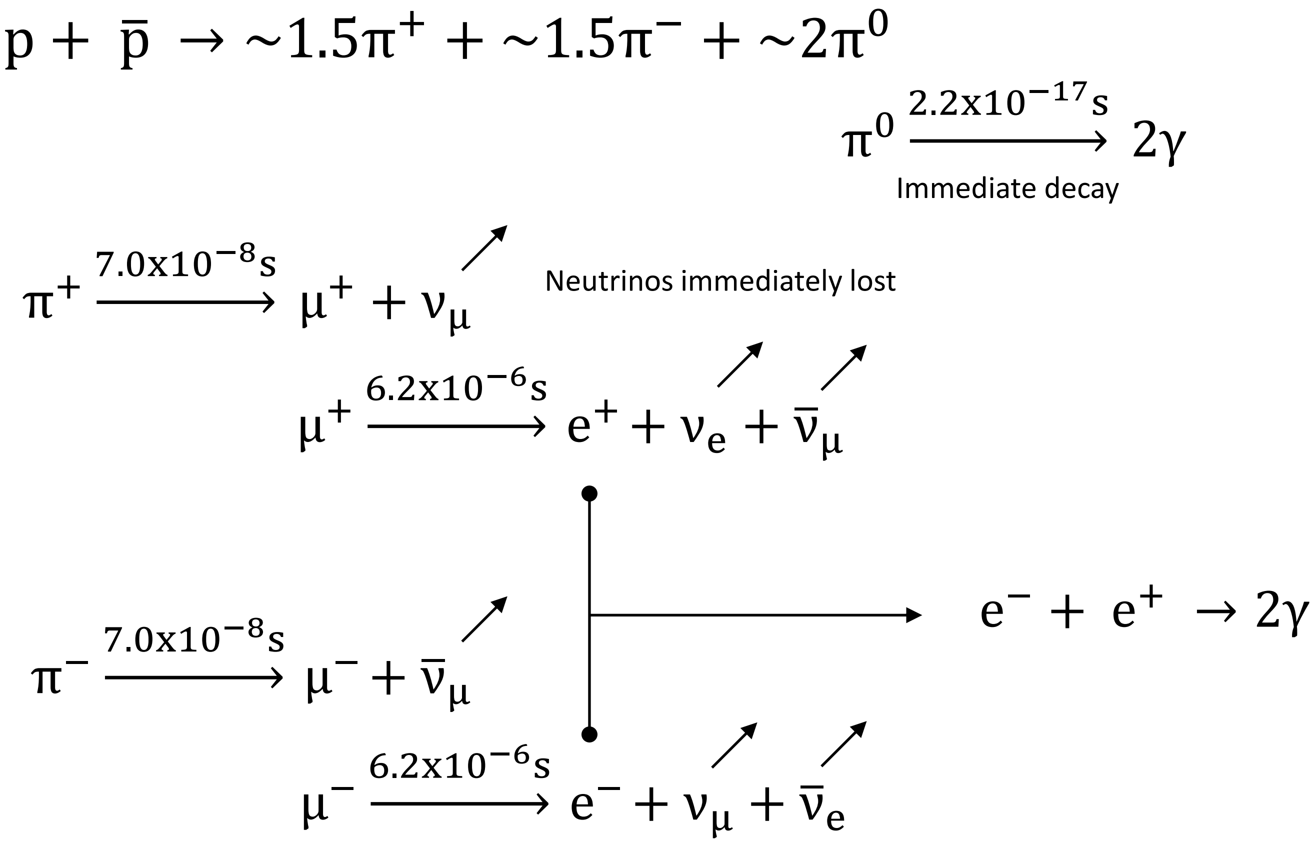
$$e^- + e^+ \rightarrow 2\gamma \quad (E_\gamma = 0.511\text{MeV})$$

- Rest mass energy per pair = $2(m_0c^2) = 1.64\text{x}10^{-13}$ J = 1.02 MeV*
- Each electron-positron annihilation results in 2 high-energy gamma rays, each with half the energy of the e^-e^+ rest mass, plus any kinetic energy carried by the pair prior to their annihilation
- γ-radiation doesn't couple well into a propellant due to low absorption cross section (long path lengths)
- Hard to collimate if we want to exhaust them directly for thrust

*Particle physics typically uses units of eV (electron volts) to describe particle energies; 1 eV = $1.6\text{x}10^{-19}$ J; very small energy units (takes ~ 82.6 kJ to boil a cup of water, or about $5\text{x}10^{23}$ eV)

Matter-Antimatter Reactions

Proton – Antiproton Annihilation Products



$$p + \bar{p} \rightarrow \sim 1.5\pi^+ + \sim 1.5\pi^- + \sim 2\pi^0$$

$$\pi^0 \xrightarrow[\text{Immediate decay}]{2.2\text{x}10^{-17}\text{s}} 2\gamma$$

$$\pi^+ \xrightarrow{7.0\text{x}10^{-8}\text{s}} \mu^+ + \overset{\nearrow}{\nu_\mu}$$

Neutrinos immediately lost

$$\mu^+ \xrightarrow{6.2\text{x}10^{-6}\text{s}} e^+ + \overset{\nearrow}{\nu_e} + \overset{\nearrow}{\bar{\nu}_\mu}$$

$$\pi^- \xrightarrow{7.0\text{x}10^{-8}\text{s}} \mu^- + \overset{\nearrow}{\bar{\nu}_\mu}$$

$$\mu^- \xrightarrow{6.2\text{x}10^{-6}\text{s}} e^- + \overset{\nearrow}{\nu_\mu} + \overset{\nearrow}{\bar{\nu}_e}$$

$$e^- + e^+ \rightarrow 2\gamma$$

Matter-Antimatter Reactions

Where Does the Annihilation Energy Go?

$$p + \bar{p} \rightarrow \sim 1.5\pi^{+} + \sim 1.5\pi^{-} + \sim 2\pi^{0}$$ *(on average)*

Total p-$\bar{p}$ rest
mass energy:
≈1880 MeV

Each π^{+} and π^{-}:
Rest mass: 139.6 MeV
Kinetic energy: ≈ 250 MeV

Each π^{0}:
Rest mass: 135 MeV
Kinetic energy: ≈ 220 MeV

690 MeV → rest mass energy of all the pions (37%)
750 MeV → total kinetic energy of the 3 charged pions (40%)
440 MeV → total kinetic energy of the 2 neutral pions (23%)
1880 MeV: $p\bar{p}$ annihilation energy (collision at rest)

- Neutral pions quickly decay into γ-rays (Eγ ≈ 130-300 MeV)
- At rest the charged pions would decay in 22 ns, but at 250 MeV they're traveling 0.93c and last for 70 ns (traveling about 21 m)

Matter-Antimatter Reactions

Charged Pion Decay:

$$\pi^+ \xrightarrow{7.0\text{x}10^{-8}\text{s}} \mu^+ + \nu_\mu$$

$$\pi^- \xrightarrow{7.0\text{x}10^{-8}\text{s}} \mu^- + \bar{\nu}_\mu$$

Each charged pion ($\pi^\pm$):

- 139.6 MeV rest mass energy
- 250 MeV kinetic energy
- ≈ 390 MeV/pion

Where does the 390 MeV/pion energy go?

- **Charged muon ($\mu^\pm$):**
  105.7 MeV → rest mass energy per muon
  192.3 MeV → kinetic energy per muon
  298 MeV per muon
- Remaining energy (92 MeV) carried away by the neutrinos (lost from the system; no interactions)
- Muons traveling 0.94c; lifetimes extended from 2.2μs to 6.2μs

Matter-Antimatter Reactions

Charged Muon Decay:

$$\mu^{+} \xrightarrow{6.2\text{x}10^{-6}\text{s}} e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$

$$\mu^{-} \xrightarrow{6.2\text{x}10^{-6}\text{s}} e^{-} + \nu_{\mu} + \bar{\nu}_{e}$$

Each charged muon ($\mu^{\pm}$):

- 105.7 MeV rest mass energy
- 192.3 MeV kinetic energy
- 298 MeV/muon

Where does the 298 MeV/muon energy go?

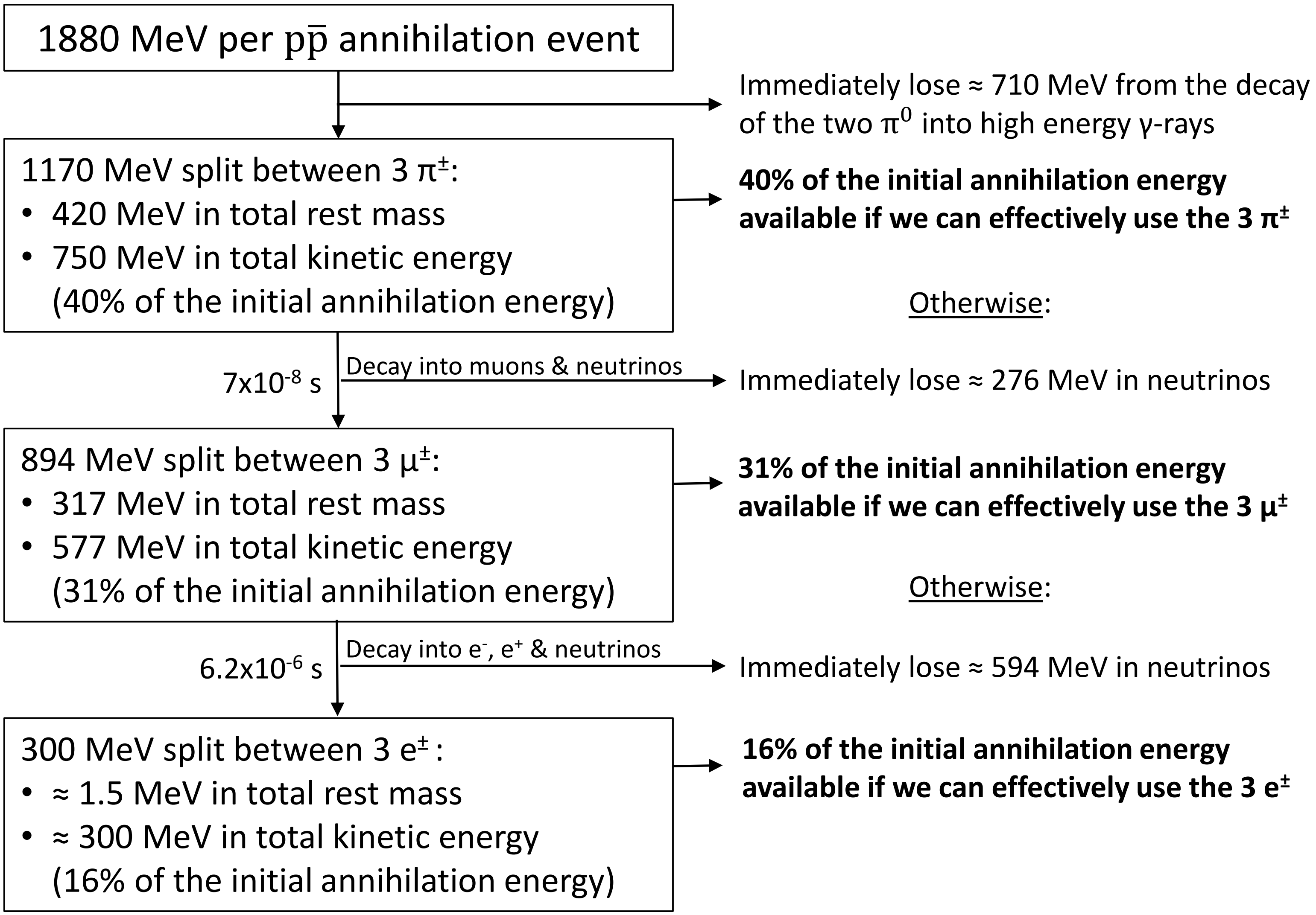
- **Positron or Electron ($e^{\pm}$):**

  0.511 MeV → rest mass energy of positron or electron
  ≈ 100 MeV → kinetic energy of positron or electron
  ≈ 100.5 MeV per electron or positron

- Remaining energy (≈ 198 MeV) carried away by the neutrinos (lost from the system; no interactions)

- Positrons may annihilate with electrons to produce γ-rays

Summary: $p\bar{p}$ annihilation



1880 MeV per $p\bar{p}$ annihilation event

Immediately lose ≈ 710 MeV from the decay of the two π^0 into high energy γ-rays

1170 MeV split between 3 $\pi^\pm$:
- 420 MeV in total rest mass
- 750 MeV in total kinetic energy
  (40% of the initial annihilation energy)

40% of the initial annihilation energy available if we can effectively use the 3 $\pi^\pm$

Otherwise:

$7\text{x}10^{-8}$ s

Decay into muons & neutrinos

Immediately lose ≈ 276 MeV in neutrinos

894 MeV split between 3 $\mu^\pm$:
- 317 MeV in total rest mass
- 577 MeV in total kinetic energy
  (31% of the initial annihilation energy)

31% of the initial annihilation energy available if we can effectively use the 3 $\mu^\pm$

Otherwise:

$6.2\text{x}10^{-6}$ s

Decay into e^-, e^+ & neutrinos

Immediately lose ≈ 594 MeV in neutrinos

300 MeV split between 3 $e^\pm$:
- ≈ 1.5 MeV in total rest mass
- ≈ 300 MeV in total kinetic energy
  (16% of the initial annihilation energy)

16% of the initial annihilation energy available if we can effectively use the 3 $e^\pm$

$\bar{\mathrm{p}}$ – Heavy Nucleus Reactions

- Antiproton annihilation with heavier nuclei results in fragmentation (and fission in very heavy nuclei)
- Morgan (1986) analyzed theoretical and experimental data of the kinetic energy of charged nuclear fragments emitted after antiproton annihilation with a nucleus
  - Fraction of annihilation energy available as kinetic energy of heavier nuclear fragments ≈ 10% for nuclei as heavy as silicon, and ≈ 20% for very heavy nuclei (including release of fission energy, e.g. splitting ^{235}U)
- Easier to couple the kinetic energy of heavier charged fragments to a working fluid, but charged pions from $\mathrm{p}\bar{\mathrm{p}}$ have higher energy fraction (40%) if we can use them

Morgan, D., "Annihilation of Antiprotons in Heavy Nuclei," Lawrence Livermore National Laboratory, Final Report, AFRPL-TR-86-011, April 1986

Antimatter Propulsion Concepts

Positrons: Sanger Photon Rocket

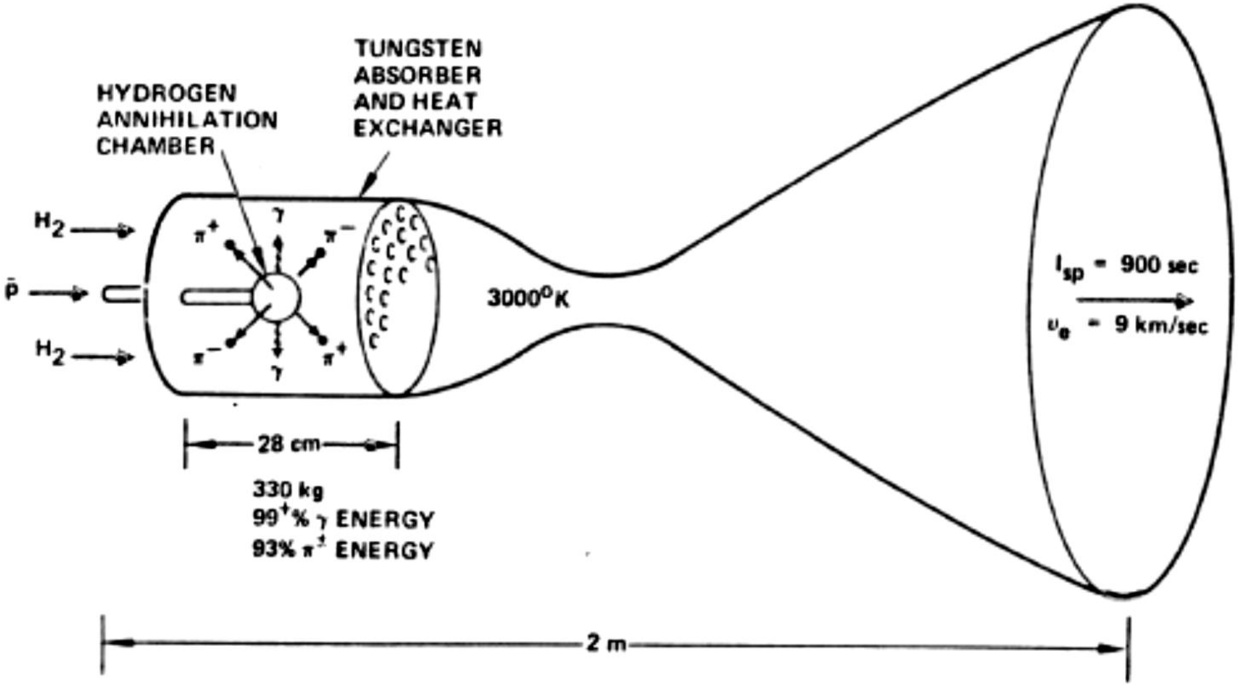
- 1953: Proposed redirecting the energetic γ-rays from the $e^- e^+$ reaction to produce thrust ($\bar{p}$ hadn't been discovered yet)
- Unfortunately there is no feasible method to reflect the high energy γ-rays, resulting in a very low engine efficiency

Option:

- The γ-rays could be used to heat a refractory absorber, which then heats a propellant flowing through a heat exchanger
- Challenge: storage density of positrons may be so low that the mass of the e^+ storage facility overwhelms potential benefits (more on antimatter storage later…)

Antimatter Propulsion Concepts

Proton-Antiproton Solid Core Engine

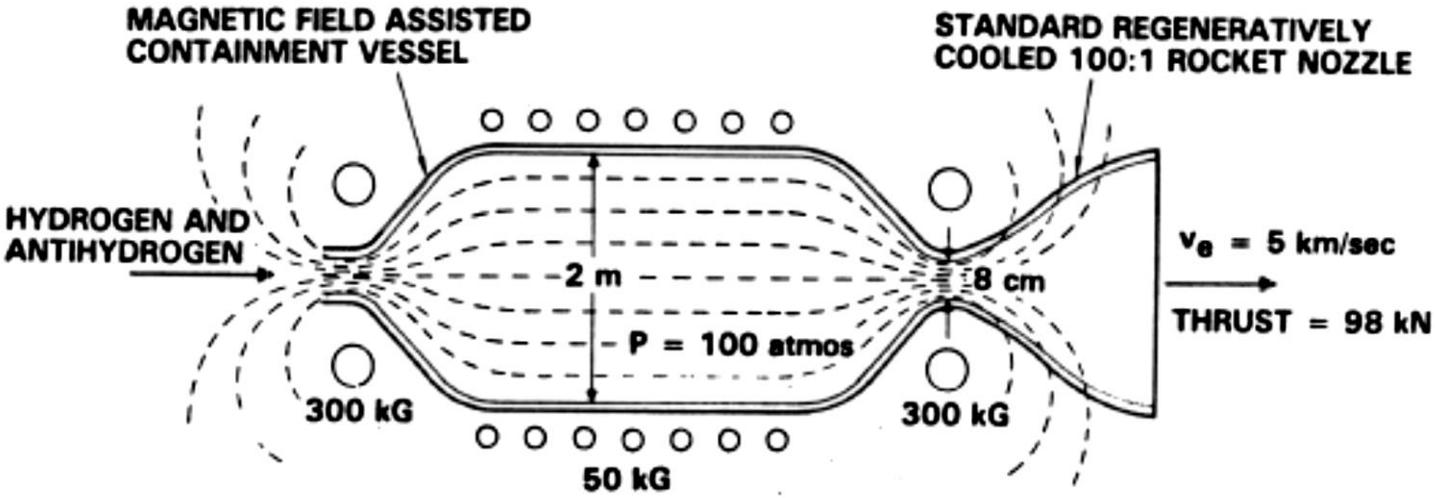


- > 90% transfer of annihilation energy to tungsten block
- Similar performance to an NTP engine (Isp ~ 900 s, high thrust)
- Typical $\bar{p}$ mass flows ~ several μg/sec (material temperature limits)

Figure: Forward, R. L., ***Antiproton Annihilation Propulsion,*** AFRPL TR-86-034, AFRPL/LKC, Edwards AFB, Ca., Sep. 1985.

Antimatter Propulsion Concepts

Proton-Antiproton Gas Core Engine

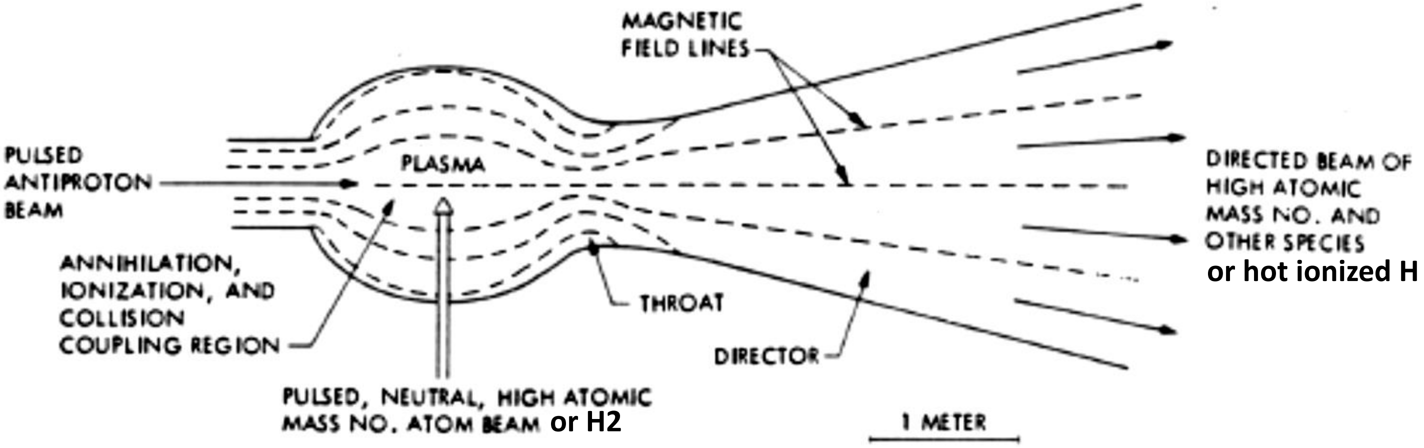


- About 35% energy transfer to the high pressure hydrogen propellant
- Specific impulse similar to chemical engines (~ 500 s), high thrust
- Variants include liquid hydrogen for better transfer efficiency
- Typical antiproton mass flow rates ~ 10’s µg/sec

Figure: Forward, R. L., ***Antiproton Annihilation Propulsion,*** AFRPL TR-86-034, AFRPL/LKC, Edwards AFB, Ca., Sep. 1985.

Antimatter Propulsion Concepts

Proton-Antiproton Plasma Core Engine

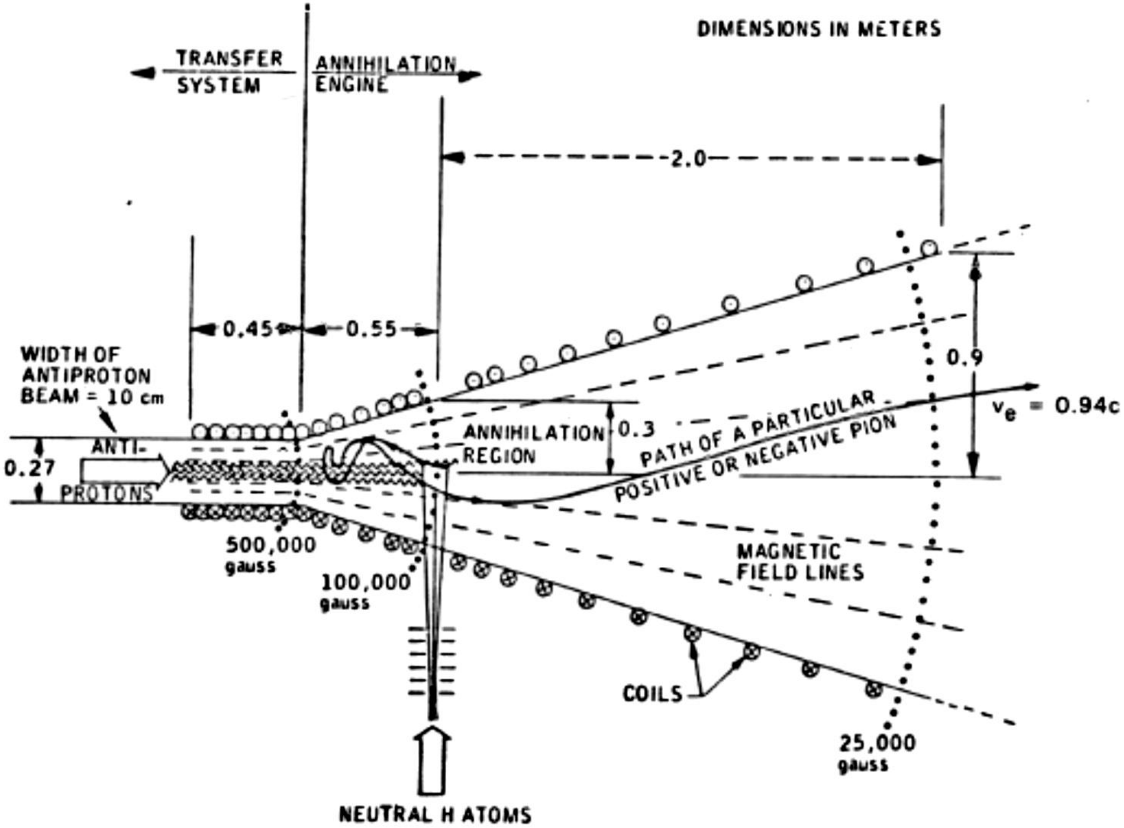


- Charged particles trapped and guided by strong magnetic fields
- Higher Isp than chemical engines (several 1000 s), moderate thrust
- Annihilation energy transferred to hydrogen is only about 1-2%*
- Typical pulse ~ 10^{18} $\bar{p}$ (depending on rep rate, ~ 100's µg/sec)
- Detailed numerical studies not yet performed for heavier elements

Figure: Forward, R. L., ***Antiproton Annihilation Propulsion,*** AFRPL TR-86-034, AFRPL/LKC, Edwards AFB, Ca., Sep. 1985
* LaPointe, M., "Antiproton Powered Propulsion with Magnetically Confined Plasma Engines," *J Prop & Power*, **7** (5), 1991

Antimatter Propulsion Concepts

Proton-Antiproton Beam Core Engine



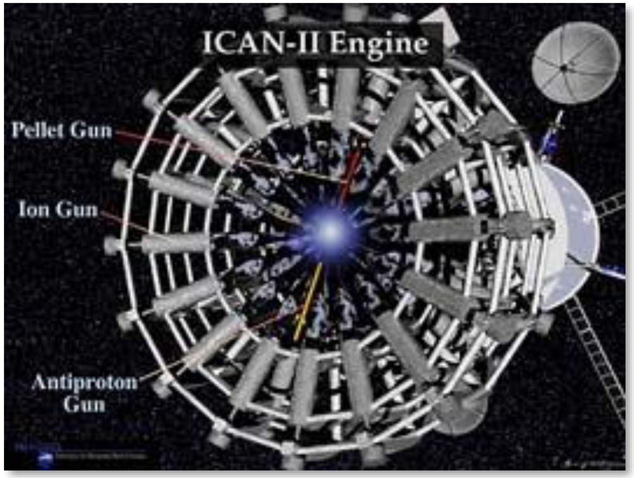
- Charged pions directed by magnetic nozzle; contain 40% of the initial annihilation energy
- Very high Isp (~ 28 million seconds) but low thrust (typically 10's N)
- Typical $\bar{p}$ flow rate ~ 100's μg/sec

Figure: Forward, R. L., ***Antiproton Annihilation Propulsion,*** AFRPL TR-86-034, AFRPL/LKC, Edwards AFB, Ca., Sep. 1985.

Antimatter Propulsion Concepts

Antiproton Catalyzed Microfission/Fusion (ACMF)

- Similar to the Orion pulsed nuclear engine concept
- Spherical fuel pellets (3 g; molar ratio D:U^{235} = 9:1) coated with 200 g of lead
- Pellet radially compressed with ion drivers; 2-ns pulse of 10^{11} $\bar{p}$ injected to initiate fission in U^{235}
- High energy fission products rapidly heat target and initiate DD fusion
- Releases ≈ 300 GJ energy
  - 83% radiation energy
  - 15% neutron energy
  - 2% ion % electron energy



https://science.nasa.gov; 1997

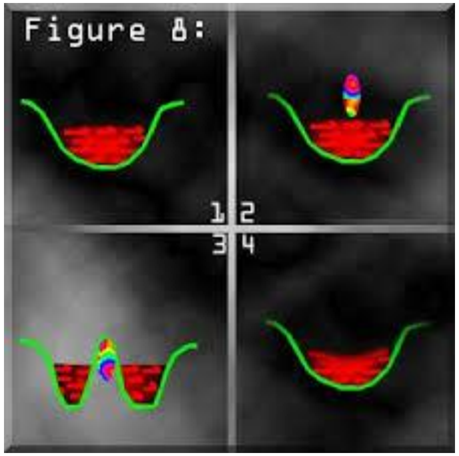
- Lead reradiates 1-keV photons, which ablate a SiC plate to produce thrust
- 1 Hz rep rate: Thrust > 100,000N, Isp > 10,000 s

G. Gaidos et al., AIAA Paper 98-3589, 1998)

Antimatter Propulsion Concepts

Antimatter Initiated Microfusion (AIM) Starship

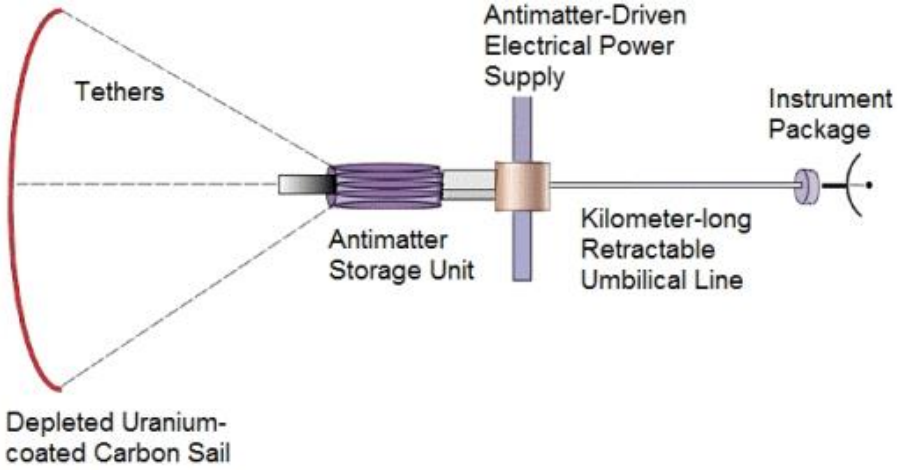
- 10^{11} antiprotons confined in Penning trap (potential well)
- 42 ng of D-He^3 fuel injected into the trap along with a small amount of fissile material
- A fraction of the antiprotons annihilate with the fissile material; the resulting energetic particles rapidly ionize the D-He^3 fuel
- Fusion initiated as the fuel is further compressed in the potential well;
  hot plasma exhausted to produce thrust
- Potential well relaxed, additional $\bar{p}$ injected, process repeats
- Produces ≈ 2-N thrust, Isp ≈ 67,000 s
- 200 Hz rep rate over 4-5 years delivers a 100-kg payload to 10,000 AU (Oort cloud) in about 50 years, using 5.7 mg of $\bar{p}$



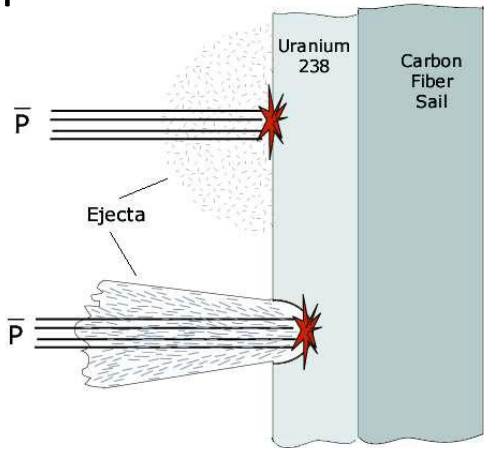
Gaidos, G et al., "AIMStar: Antimatter Initiated Microfusion for Pre-cursor Interstellar Missions," Acta Astronautica ***44****, (2–4), pp.183–186, 1999*

Antimatter Propulsion Concepts

Antimatter Driven Sail



- Antiprotons directed at uranium sail coating
- Resulting fission products traveling ≈ 10^7 m/s
- Isp ≈ 10^6 s



Depositing $\bar{p}$ deep in the uranium produces multiple atom ejections, increasing thrust and reducing Isp

Preliminary mission analysis:

- 10 kg instrument payload could be sent to 250 AU in 10 years using 30 mg of $\bar{\mathrm{H}}$
- A similar probe could be sent to Alpha Centaur in 40 years using grams of $\bar{\mathrm{H}}$

Howe, S., "Antimatter Driven Sail for Deep Space," NASA Institute for Advanced Concepts, Phase II Study, 2004

Challenges: Production

Positrons:

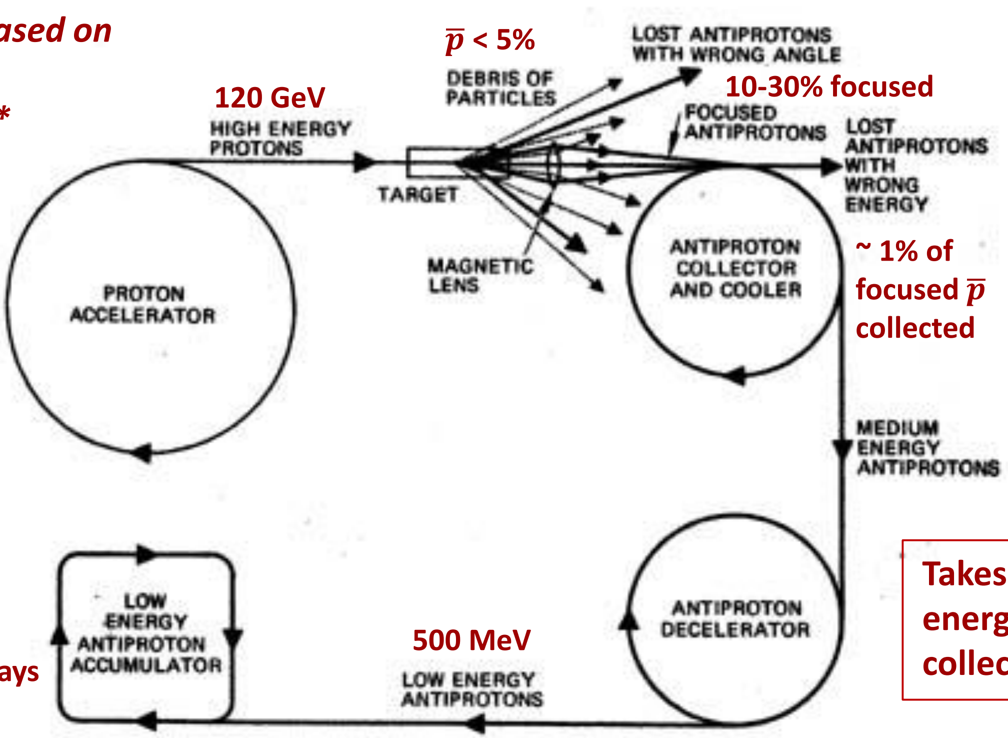
- **Radioactive emitters (β^+ decay)**
  - Proton in radionuclide nucleus → $n + e^+ + \nu_e$
  - Short-lived isotopes created using cyclotrons
    - β^+ emitters used in PET scans (e.g. C^{11}, N^{13}, F^{18}, etc.)
  - Rare in nature: 0.001% of $K^{40} \rightarrow Ar^{40}$ via β^+ decay
    - 1 banana produces a positron ~ every 75 minutes!
- **Pair creation (e^+e^-)**
  - Requires focusing $2m_oc^2$ of energy in a very small volume to create a particle-antiparticle pair
    - Particle accelerators (colliding beams with targets)
    - Vacuum pair creation by energetic photons (laser; γ-rays)
    - Cosmic rays colliding with nuclei in the atmosphere (cascade into pions, muons, energetic γ-rays and e^+e^- pairs)

Production

Antiprotons:

- **Created in high energy particle accelerators**
  - Generally not optimized for antiproton production
- **Collide a high energy proton beam with a target:**

*Estimates based on prior FNAL capabilities**



120 GeV

$\overline{p} < 5\%$

10-30% focused

~ 1% of focused $\overline{p}$ collected

500 MeV

Circulate ~ 10^{12} $\overline{p}$ (picograms) for days

Takes ~ 10^5 high energy protons to collect 1 antiproton

*Forward, R and J. Davis, Mirror Matter: Pioneering Antimatter Physics, Wiley Science, 1998

How Much Has Been Made?

Total amount of antiprotons produced:

- FermiLab (US) ≈ 15 ng
- DESY (Germany) ≈ 2 ng
- CERN (Switzerland) ≈ 1 ng

How much annihilation energy is this?

- $\mathrm{E} = 2\mathrm{m_o c^2} \approx 3.2 \times 10^6\ \mathrm{J}$
- Enough to boil about 1 liter of water

Enough to do physics experiments and ground based propulsion concept testing

- Not optimized for efficient antiproton production
- Interesting potential spin-off for beam cancer therapy
  - Focused beams deposit kinetic energy to heat tumors, with an extra burst of local energy gained from antiproton annihilation

Challenges: Cost

Antiproton Production Cost Estimate

Schmidt et al. estimated the energy cost (K) as:

$$\mathbf{K} = \mathbf{k}_{\mathbf{grid}} \mathbf{E}_{\mathbf{grid}}$$

- $\mathbf{k}_{\mathbf{grid}}$ = unit cost of electrical power ($/kW-hr)
- $\mathbf{E}_{\mathbf{grid}}$ = $M_a c^2/\eta_{tot}$ = energy required to create an amount of antimatter M_a with efficiency η_{tot}
- Efficiency $\boldsymbol{\eta}_{\mathbf{tot}}$ can be expressed as $\boldsymbol{\eta}_{\mathbf{tot}} = \boldsymbol{\eta}_{\mathbf{conv}} \boldsymbol{\eta}_{\mathbf{grid}}$, where:

  $\boldsymbol{\eta}_{\mathbf{conv}}$ = efficiency of the antimatter production and collection process

  $\boldsymbol{\eta}_{\mathbf{grid}}$ = electrical efficiency of the accelerator system

Schmidt, G. et al., "Antimatter Requirements and Energy Costs for Near Term Propulsion Applications," *J. Power and Propulsion*, 16 (5), Sep–Oct 2000

Cost Estimate:

Substituting values yields:

$$\mathbf{K = \frac{k_{grid} M_a c^2}{\eta_{conv} \eta_{grid}}}$$

Rough estimate based on FermiLab values:

- **k_{grid}** = wall plug power ≈ **\$0.10/kW-hr** (**\$2.8x10^{-8}/J**)
- **M_a** = antimatter rest mass collected (kg)
- **η_{grid}** = electrical efficiency of the accelerator system ≈ **5x10^{-3}**

  14 MW of power required to deliver 5x10^{12} 120-GeV proton beam every 1.5 s onto production target → power in beam ≈ 6.4x10^{4} W; 6.4x10^{-4}/14x10^{6} ≈ 5x10^{-3}
- **η_{conv}** = efficiency of production and collection process≈ **7.8x10^{-8}**

  Rest mass energy of $\bar{p}$ = 938 MeV = 9.38x10^{8}/$\bar{p}$. Energy to create and collect one $\bar{p}$ = 120 GeV/proton x 10^{5} p/$\bar{p}$ = 1.2x10^{16} eV/$\bar{p}$; 9.38x10^{8}/1.2x10^{16} = 7.8x10^{-8}

$$\frac{\mathbf{K}}{\mathbf{M_a}} = \frac{k_{grid}\, c^2}{\eta_{conv}\eta_{grid}} = \frac{(\$2.8\times10^{-8}/\mathrm{J})\left(3\times10^{8}\,\mathrm{m/s}\right)^2}{(5\times10^{-3})(7.8\times10^{-8})} \approx \frac{\$6.4\times10^{18}}{\mathrm{kg}} = \boxed{\frac{\mathbf{\$6.4\times10^{12}}}{\mathbf{mg}}}$$

Schmidt, G. et al., *J. Power and Prop*, 16 (5), Sep–Oct 2000

How Much Do We Need?

ΔV for representative missions of interest:

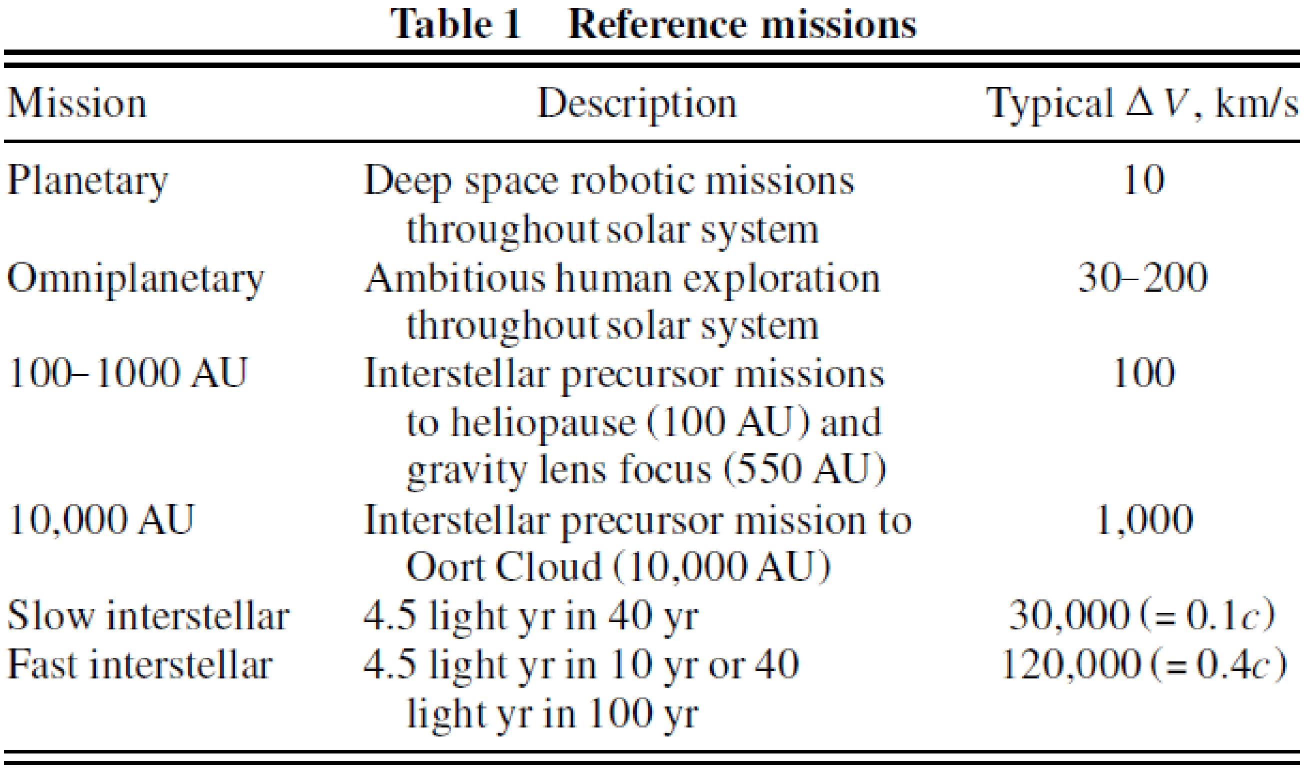
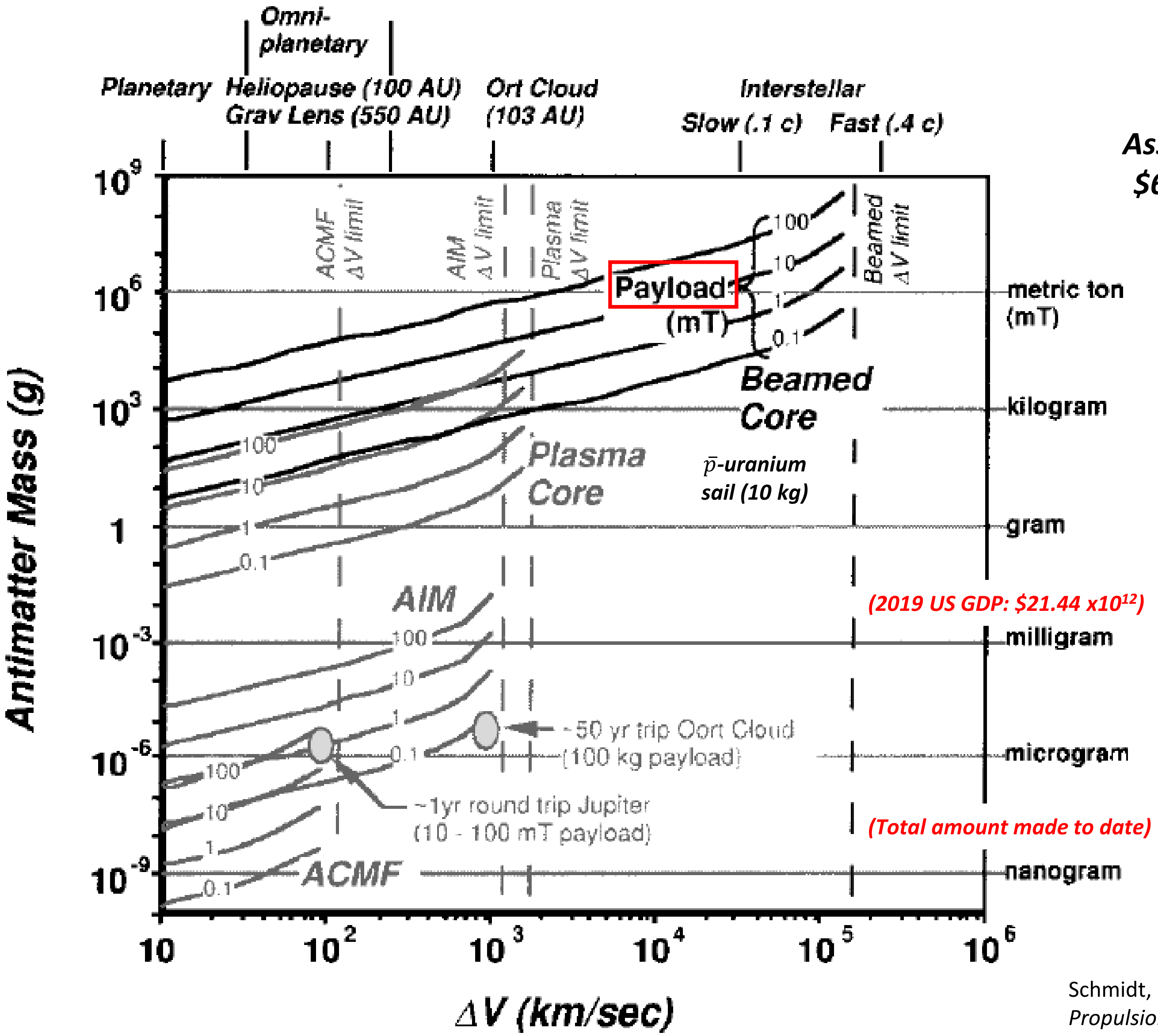


Table 1 Reference missions

Mission	Description	Typical ΔV, km/s
Planetary	Deep space robotic missions throughout solar system	10
Omniplanetary	Ambitious human exploration throughout solar system	30–200
100–1000 AU	Interstellar precursor missions to heliopause (100 AU) and gravity lens focus (550 AU)	100
10,000 AU	Interstellar precursor mission to Oort Cloud (10,000 AU)	1,000
Slow interstellar	4.5 light yr in 40 yr	30,000 ($= 0.1c$)
Fast interstellar	4.5 light yr in 10 yr or 40 light yr in 100 yr	120,000 ($= 0.4c$)

Schmidt, G. et al., “Antimatter Requirements and Energy Costs for Near-Term Propulsion Applications,” *J. Power & Propulsion*, 16 (5), Sep–Oct 2000

Amount of Antimatter Required



(2019 US GDP: $\$21.44\text{x}10^{12}$)

(Total amount made to date)

Assuming a cost of $\$6.4\text{x}10^{15}$/g of $\bar{p}$:

$\$6.4\text{x}10^{21}$

$\$6.4\text{x}10^{18}$

$\$6.4\text{x}10^{15}$

$\$6.4\text{x}10^{12}$

$\$6.4\text{x}10^{9}$

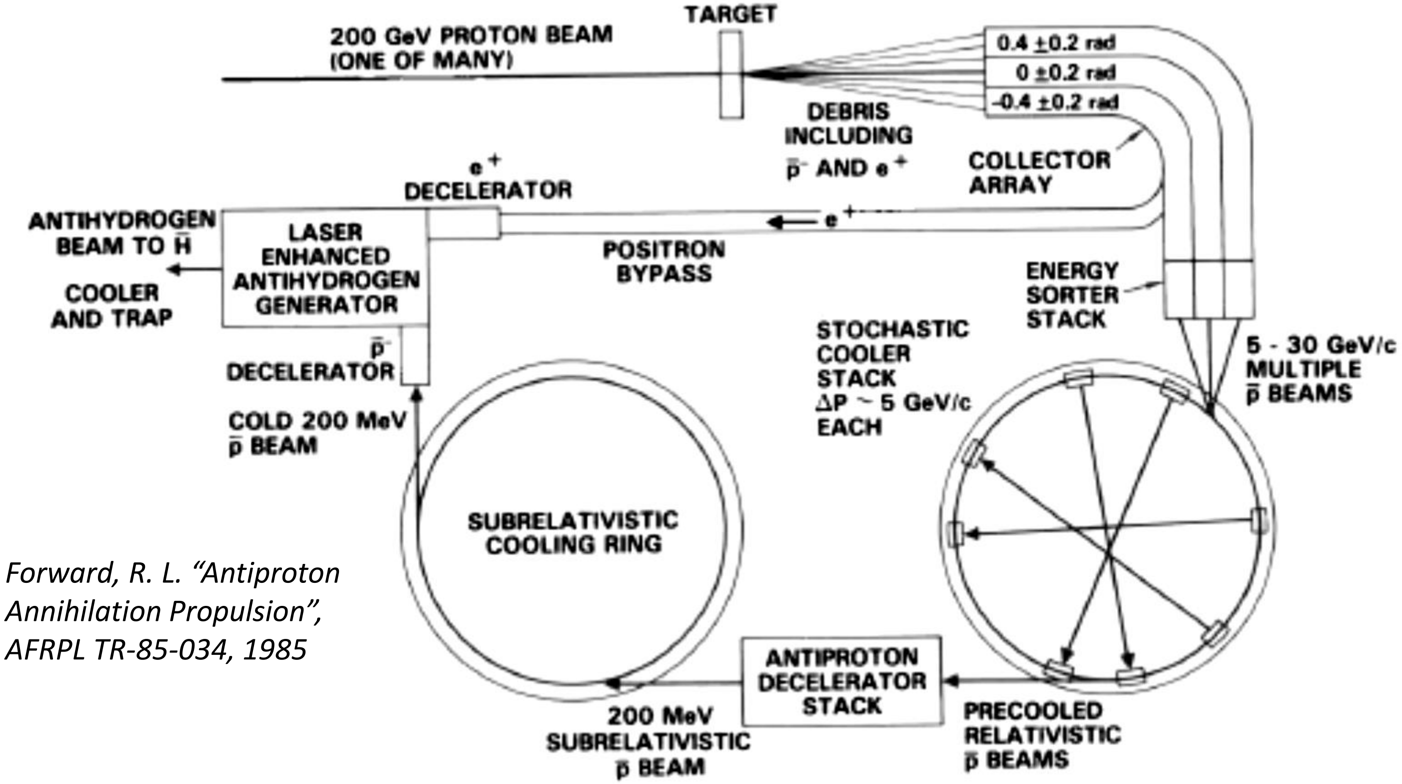
$\$6.4\text{x}10^{6}$

Schmidt, G. et al., *J. Power and Propulsion*, 16 (5), Sep–Oct 2000

Improving Production

- **Accelerator facilities are not designed as antiproton factories**
  - A full year of dedicated operation at FNAL, assuming prior capabilities, would produce ≈ **ng/year**
- **Improvements to traditional facilities could increase $\bar{p}$ production to ≈ µg/year**
  - Use thinner targets for more focused $\bar{p}$ beams
  - Improve antiproton collection & storage methods
  - Optimize proton acceleration energy and duty cycle
- **1998 Rand Corp study evaluated the cost of a dedicated ground-based facility to produce ≈ several mg/year**
  - Facility cost ≈ \$(3–10)x10^9 to build
  - Could bring cost down to \$6.4x10^{10} per gram
  - *Proceedings of the Rand Workshop on Antiproton Science and Technology,* World Scientific, Singapore, 1988

Antiproton Factory (R. Forward)



Forward, R. L. "Antiproton Annihilation Propulsion", AFRPL TR-85-034, 1985

- Uses high efficiency linear accelerator for multiple high energy proton beams
- Positrons sent to decelerator, then to laser-enhanced antihydrogen generator
- Antiprotons collected using an array of wide angle collecting lenses and sent to stochastic coolers, then decelerator, then cooling ring before being sent to the antihydrogen generator to combine with positrons to make $\bar{\mathrm{H}}$ atoms
- Very optimistic cost estimate: **$\$10^{10}$/g** (comparable to Rand study)

Space-Based Production

Potential advantages:

- Hard vacuum
- Abundant solar power
- Fuel vehicles in space (vs. launching $\bar{p}$ from ground)

Challenges:

- Requires a lot of infrastructure (accelerator, collector, storage rings, etc.)
- Requires a large amount of solar arrays (100’s MW)
- Will be expensive to launch, assemble, operate and repair

Capture antimatter already in space?

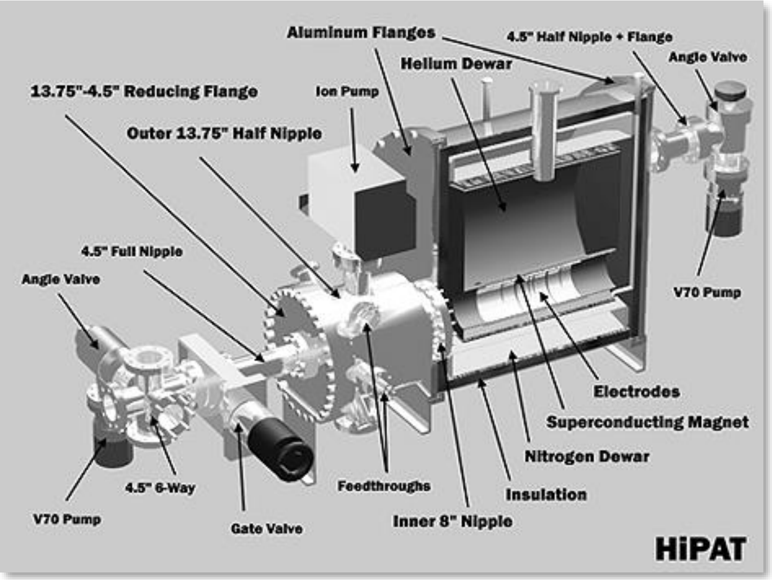
- Very low density cloud of antimatter particles trapped in Earth’s van Allen belts; capture for propulsion?

  (e.g. https://www.sciencemag.org/news/2011/08/antimatter-belt-found-circling-earth)

Challenges: Storage

Density of antiprotons or positrons limited by space charge

- Facility accumulator rings can hold ≈ 10^{12} $\bar{p}$ (1.7×10^{-12} g, or picograms) for indefinite periods of time
- A portable High Performance Antiproton Trap (HiPAT) developed by NASA was designed to hold 10^{12} $\bar{p}$ for up to 18 days using a Penning-Malmberg electromagnetic trap
  - For $\bar{p}$ testing at MSFC
  - Built but never used
- 1000s of traps required to hold nanograms of antimatter



Solid Antihydrogen

$\bar{\mathrm{H}}$ atoms are currently made and trapped; cool and cluster to create solid $\bar{\mathrm{H}}$ to improve storage density?

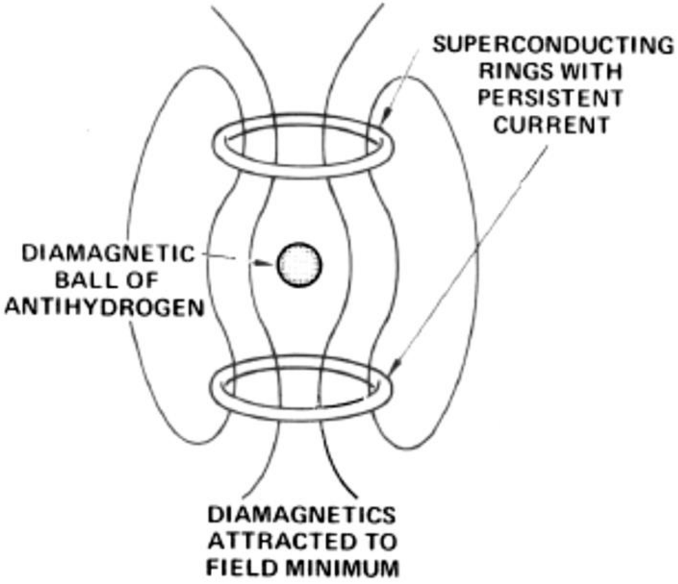
- Can’t touch walls, so nucleation approaches used with normal hydrogen won’t work; need to nucleate directly from cold, trapped antihydrogen atoms
- Laser cool $\bar{\mathrm{H}}$ atoms to form and trap $\bar{\mathrm{H}}$ molecules, accumulate sufficient molecules to begin condensing into microcrystals of $\bar{\mathrm{H}}$ ice?
- Cluster ion formation, in which large numbers of $\bar{\mathrm{H}}$ atoms cluster around a single charged $\bar{\mathrm{p}}$; continue adding $\bar{\mathrm{H}}$ atoms to crow cluster into microcrystal?

Critical area that still needs a lot of work!

Solid Antihydrogen Storage

Once created, solid antihydrogen can be more readily stored and transported

- Hydrogen and antihydrogen are diamagnetic
  - A weak magnetic dipole moment is induced in the direction opposite to an applied magnetic field
- Solid antihydrogen can be passively trapped in a “magnetic bottle”
- Alternative: electrostatic levitation between two charged electrodes
  - Weak UV light used to liberate positrons to provide a surface charge on the solid $\overline{\text{H}}$ ice



Forward, R and J. Davis, Mirror Matter: Pioneering Antimatter Physics, Wiley Science, 1998

Delivering to the Engine

Feasible options exist to remove antiprotons or $\overline{\mathrm{H}}$ microcrystals from storage

- **If suspended as solid ball of $\overline{\mathrm{H}}$ ice:**
  - UV laser to drive off some positrons
  - Intense electric field to pull of charged antiprotons
  - Electromagnetically channel to annihilation engine
- **If stored as cloud of frozen $\overline{\mathrm{H}}$ microcrystals:**
  - UV light drives positrons from selected microcrystal
  - Electric fields pull charged microcrystal from the trapped cloud
  - Charged microcrystal electromagnetically channeled to the annihilation engine

Vehicle Design

Things to consider:

- Depends on the concept, but in general:
  - Storage during launch and in-space acceleration; methods to transport $\bar{p}$ or e^+ to the engine
  - Magnet requirements (magnetic nozzles, etc.)
  - Radiation shielding (high energy γ-rays will damage material structures, electronics and humans)
  - Thermal radiators (need to reject a significant amount of waste heat; may be large and massive)
  - Vehicle support structures (trusses, tanks, etc.)
  - Payload placement (far away from radiation)
  - Additional propellant (to interact with antimatter)
  - Number of launches and in-space assembly

Summary

- High level look at some antimatter propulsion concepts and corresponding challenges
- Current collider facility antiproton production rates are low (ng/year) and very expensive (≈ $\$10^{12}$/mg)
- A dedicated antiproton factory could conceivably make several mg/year to grams/year of antimatter at lower cost ($\$10^{7}$/mg); still very expensive for concepts requiring grams of antimatter
- Methods for high density antimatter storage need to be developed and demonstrated
- Vehicle designs need to account for shielding and thermal radiators – may be big mass drivers
- Both you and bananas are radioactive

Short List of References

Some popular texts:

- Frank Close, Antimatter, Oxford University Press, 2009
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A few select references:

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Q&A

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