Antimatter Initiated Microfission/fusion (AIM) Space Propulsion

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For most people space travel is in the back of their mind, surfacing only during a "Mission to Mars" movie commercial. The typical person may wonder if they will get to see live CNN footage of the first steps onto the great red planet within their lifetime. However, the thoughts of the more imaginative probably begin with a Mars landing and quickly proceed to interstellar missions travelling at nearly the speed of light. The interstellar dreamer helps sustain a constant influx of new propulsion schemes that provide hopes of someday reaching past Mars quickly and easily. One such hopeful scheme is called Antimatter Initiated MicroFission/Fusion (AIM). AIM is a fusion propulsion concept that is a hybrid of fission and fusion technologies that incorporates an exotic particle called the antiproton. In this concept, antiprotons are manipulated in order to initiate the difficult process of burning fusion fuels. However, the exotic nature of antiprotons presents special challenges to the development of AIM technology. In this paper I will present an overview of the AIM concept and discuss its viability as a space propulsion mechanism.

The first clue to the existence of antimatter was uncovered early in the 19th century by a physicist named Paul Dirac. The physics community during this era was rich with exiting, unconventional new theories such as Einstein's theory of relativity and Erwin Schrodinger's wave treatment of particles eventually known as quantum mechanics. Schrodinger's quantum theory accurately predicted many previously unexplained experimental phenomena, however, his theory only applied to non-relativistic, "slow moving" particles. In 1929, Paul Dirac proposed a set of equations describing the behavior of electrons by using a combination of the theories of relativity and quantum mechanics. There where two possible solutions to the equations; 1) an

electron with positive energy, and 2) an electron with negative energy.[3] Dirac formulated that an electron with negative energy would behave identical to one with positive energy if that particle had a positive charge. Dirac then proposed that such particles with opposite charges existed and called them antiparticles. Soon after (1932), physicist Carl Anderson discovered the existence of the antielectron, later named the positron, in a cloud chamber designed to detect cosmic rays. Cosmic rays interacting with the detector caused pair-production events which proved the existence of the antielectron as well as provided support for Einstein's famous formulation $E=mc^2$. Because the rest mass of a proton is approximately 1835 times that of an electron, much more energy would be needed to produce a proton-antiproton pair. At least 1.88 GeV would be necessary to produce such a pair and prove the existence of the antiproton. This energy was not attainable until the fifties when a particle accelerator called the Bevatron was constructed at the Lawrence-Berkeley Laboratory in California. Physicists Owen Chamberlain, and Emilio Segre where able to detect the existence of the antiproton in 1955 by colliding high energy proton beams with high Z targets.

Antimatter has been described as the "mirror image" of matter.[3] The positron and the antiproton have the exact mass and spin of their counterparts, as well as the exact opposite charge. Compared with normal matter the magnetic moment of antimatter is reversed. In principle, anti-atoms could be made that consist of anti-particles such as a positron and antiproton forming antihydrogen. Matter and antimatter have a unique relationship between one another. When matter comes in contact with antimatter an annihilation reaction occurs in which both particles are converted into energy that is equal to the sum of their rest energies according to $E=mc^2$. For example, the annihilation

of an electron and positron results in two 0.511 MeV gamma rays. When a proton and

antiproton ($\bar{p}$) annihilate the result is a combination of charged and uncharged particles

called pions. Charged pions ($\pi^{\pm}$) have a rest mass energy of 139.6 MeV and neutral

pions (π^{o}) have a rest mass of 135 MeV. [9] Pions belong to the "meson" family of

particles that are part of the exchange force model. This model postulates that nucleons

apply forces on one another between extremely short distances by exchanging particles

that carry the nuclear force.[9] The proton-antiproton reaction products can be seen below.

$$\bar{p} + p \rightarrow \begin{array}{l} 2\pi^{O} \rightarrow 2(\gamma + \gamma) \\ 1.5\pi^{+} \rightarrow 1.5(\mu^{+} + \upsilon_{\mu}) \\ 1.5\pi^{-} \rightarrow 1.5(\mu^{-} + \bar{\upsilon}_{\mu}) \end{array}$$

$$\Downarrow$$

$$\begin{pmatrix} \mu^{+} \rightarrow e^{+} + \bar{\upsilon}_{\mu} + \upsilon_{e} \\ \mu^{-} \rightarrow e^{-} + \bar{\upsilon}_{e} + \upsilon_{\mu} \end{pmatrix} \Rightarrow e^{+} + e^{-} + \text{neutrinos} \rightarrow \gamma + \gamma + \text{neutrinos}$$
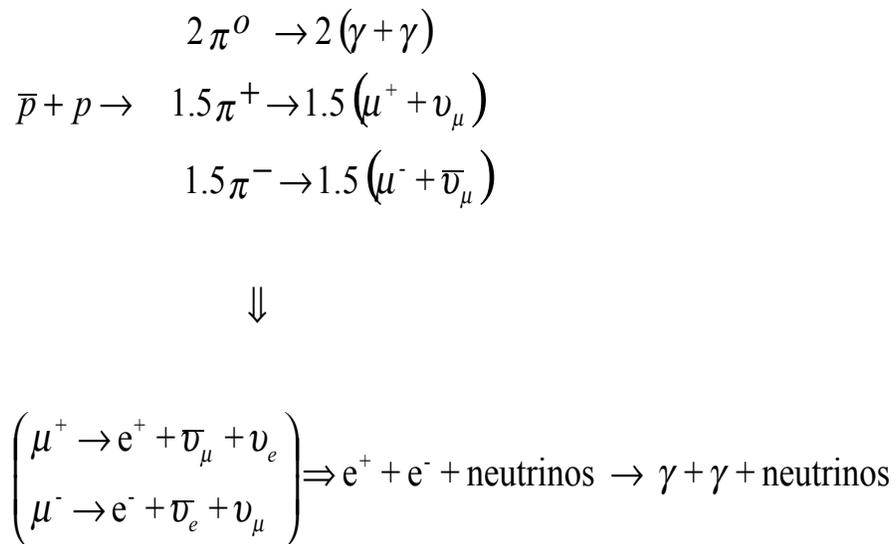
Neutral pions decay almost instantaneously with a mean life of 84 x 10^{-18} seconds into

two 200 MeV gamma rays.[12] Charged pions decay with a mean life of $\approx$ 70 nanoseconds

into muons ($\mu^{\pm}$) and neutrinos (ν). Charged muons are considered to be like "heavy"

electrons with a rest mass of 105.7 MeV, while neutrinos are neutral and essentially

massless. Muons decay into electrons, positrons and neutrinos. The mean lifetime of a

muon is approximately 6 microseconds. The electrons and positrons produced from

muon decay will inevitably annihilate to produce two 0.511 MeV gamma photons. The

energy per unit mass of reactants, or specific energy, of this annihilation reaction is 9 x

10^{16} J/kg. This is the highest specific energy of any known reaction, which gives

antimatter potential as a fuel for propulsion schemes.

A spacecraft engine designed around the AIM concept receives its propulsive

energy from fusion reaction products. Therefore, before describing the AIM concept in

detail, it will first be useful to explain why fusion in general is a popular concept for

space propulsion. The first and most general fuel parameter to analyze is the energy

density of fuels. The energy density, or specific energy, is the amount of energy released

per mass of reactants. In general, a larger specific energy results in a smaller mass of fuel

needed for a specific mission. Therefore, a large energy density could allow a spacecraft

to carry excess fuel to add to mission flexibility. Figure 1 shows the specific energy of

various space propulsion fuels.
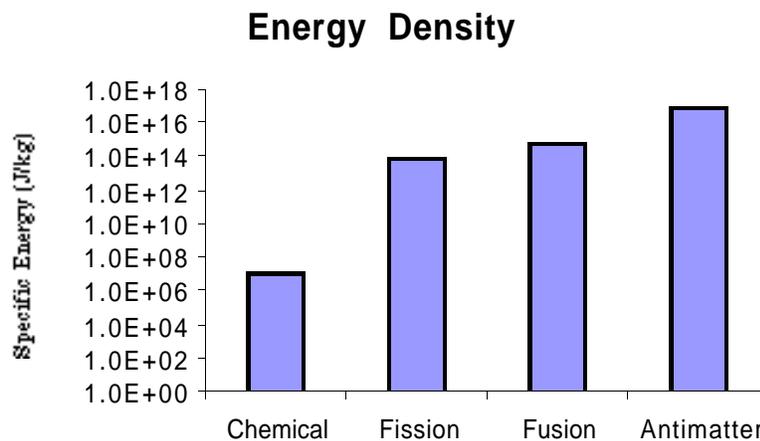
Figure 1. Energy density (J/kg) for various Reactions.[5]

The comparatively low energy density of chemical reactions explains the incentive to develop alternative fuel technologies. Antimatter annihilation has by far the greatest potential as a propulsion fuel. Proton-antiproton annihilation yields 1.8×10^{14} Joules per gram of antiprotons which is 10^{10} times greater that an Oxygen-Hydrogen reaction and approximately 100's greater than any fission or fusion reaction.[12] The annihilation of 1 gram of antihydrogen with 1 gram of Hydrogen would release approximately the same amount of energy as 23 Shuttle external tanks.[12] However, there are many more factors to examine when comparing propulsion fuels. The abundancy of a fuel is an important long-term factor. Antimatter is produced now in extremely small amounts by an energy intensive process. A spacecraft fueled solely by antimatter would have fuel needs that greatly exceed current and near future capabilities and would be an extremely inefficient means of routine space travel. Fission fuels, such as Uranium, are also a limited resource that will most likely expire within a couple of centuries, especially as it is currently burned as a terrestrial energy source. Fusion fuels, on the other hand, are quite abundant. Deuterium, for example, exists in a stable fashion in all natural waters to the extent of 1 part in 6,660 resulting in a nearly unlimited resource.[2] He-3, another fusion fuel, has been found to exist on the moon in potentially large quantities. Another advantage of Fusion over fission is inherent radioactivity. Fusion products are light and generally stable, whereas fission products are extremely radioactive. Radioactivity is not only a potential health risk but shielding the radioactivity equates to mass which is a definite

penalty in respect to space travel. It has also been shown that efficient (fast transport and high payload fractions) solar system travel requires high exhaust velocity (10^5-10^6 m/s) and low thrust/weight ratios (10^{-3}).[11]   Many fusion concepts are better equipped to meet this criteria than competing fission and chemical schemes.[11]

Fusion energy has been the subject of scientific research for many decades, which has resulted in a number of fusion plasma confinement schemes. Currently, there are two main divisions of fusion research. One is called Inertial Confinement Fusion (ICF). ICF is a pulsed concept that involves pellets of fuel that are heated and compressed to fusion ignition levels by many beams of energy such as lasers or ion beams. Another scheme, Magnetic Confinement Fusion (MCF), aims at using large magnetic fields to confine and heat fusion plasmas in a steady-state fashion. Thus far, both concepts have been unable to obtain complete burns of fusion fuels. Evenly distributing laser beam energy over an ICF target has proven to be a difficult task, and many unforeseen plasma instabilities in both concepts have retarded progress. Unlike terrestrial applications, the mass of a system must be minimized for efficient space travel. Many MCF concepts are generally quite massive, while ICF laser drivers are also massive. The AIM confinement scheme has similarities to both ICF and MCF. Like ICF, AIM uses "targets" of fuel that are injected into a reaction area. AIM also utilizes magnetic fields to confine an ionized target. Unlike the traditional schemes, AIM uses antiprotons to ionize and heat the fusion fuel. This method of plasma heating is attractive because it eliminates the need for massive driver systems that are needed in ICF concepts, resulting in a potentially lightweight system. Before giving a detailed outline of the unique process of AIM confinement, it will be useful to first review the type of fuel proposed for use in AIM engines.

As with most fusion confinement schemes Deuterium (D), Tritium (T), and Helium-3 (^{3}He) are the main fuels being considered. The fusion reactions of interest here are D-T and D-^{3}He reactions. The reaction products and their energies are given below.

$$D + T \;\; ---> \;\; \text{neutron (14.1 MeV) + Alpha particle (3.5 MeV)}$$

$$D + {^3}He \;\; ---> \;\; \text{Proton (14.7 MeV) + Alpha particle (3.6 MeV)}$$

Both reactions have advantages and disadvantages. The D-T reaction has a large cross-section at much lower energies than the D-^{3}He reaction. However, the D-^{3}He reaction produces only charged particles, which are much easier to convert to propulsive energy than the neutrons produced in a D-T reaction. Also, neutron radiation damage to spaceship components and human tissue is a much larger problem with neutrons. For the AIM concept, the fuel (D-T, or D-^{3}He) will be in liquid droplet form with a 2% molar admixture of U-238.[8] In the following discussion, the basic physics of the AIM concept is described in reference to a D-^{3}He-^{238}U liquid fuel droplet.

A Penning trap device has been proposed by the Penn State LEPS group that creates a cloud of 10^{11} antiprotons within an area less that 2 cubic centimeters to serve as the reaction area.[8] The Penning trap is a device that uses magnetic and electric fields to "trap" a charged particle within certain spatial limits. Figure 2 shows a schematic of a basic Penning trap. The base of the trap is a solid metal ring in which the inside has a hyperbolic shape. The ring is capped at the top and bottom by hyperbolic-shaped electrodes. This structure is then place inside a vacuum chamber within the bore of a superconducting magnet at liquid helium temperatures.[3] The superconducting magnet creates a magnetic field that is directed through the axis of the trap. The caps are held at a negative potential to prohibit the antiprotons from escaping axially. The antiproton will

feel a force to the toward the positively biased ring, but as it moves toward the ring the

magnetic field will exert a force that keeps the antiproton moving in a circular motion

that never reaches the rings edge.

Figure 2. Basic Penning Trap Diagram. [3]

The antiprotons are confined radially by a 20T magnetic field in the Penn State

proposal. Antiprotons are trapped axially by a 10 keV space charge potential provided by

the top and bottom electrodes. The Penning trap arrangement is shown in the figure

below.

Figure 3. 10 kV potential well for axial trapping of antiprotons to create reaction area. [8]

A 42 ng fuel droplet (D-^{3}He-^{238}U) is injected into the cloud of antiprotons.[8] Annihilation

occurs immediately as the droplet reaches the surface of the antiproton cloud. The

annihilation with U-238 causes fission to occur. It has been estimated by the Penn State

group that the number of annihilations occurring will be on the order of 5×10^8

annihilations in 1 nanosecond.[8] The fission fragments produced have a range of

approximately 45µm in the fuel mixture, and will deposit approximately 5×10^{13}

Watts/cm^3 over the fuel droplet.[8] This energy deposition is comparable to a 1kJ,

1nanosecond laser depositing energy over a 200µm ICF target.[8] Also, it has been shown

that the fission fragments produced by antiproton induced fission are not radioactive.[8]

The absence of radioactive fission products eliminates the mass penalty of additional

shielding requirements. The energy deposited fully ionizes and heats the fuel droplet.

The ions are confined to the center of the reaction area by a weakly nested potential well,

while the antiprotons and electrons are confined just off-center. In order to push the fuel

to a full burn, the Deuterium and Helium-3 ions must be compressed to high density for a

period of time long enough to satisfy Lawson's criterion. According to Lawson's

Criterion, the product of the plasma density (n) and the plasma confinement time (τ) must

exceed a certain number in order to achieve a full fusion burn. This number is dependent

upon the energy released in the particular fusion reaction, ion velocities, and the fusion

reaction cross-section.[2] For D-^{3}He fuel, nτ must exceed 5×10^{15} s/cm^3.[8] To obtain high

densities, a strongly nested potential well is applied as shown in the figure 4.

Estimates from Kramer, et al (AIMstar) show that the application of a 600 kV

potential will result in a 100 keV ion plasma temperature, 6×10^{17} ions/cm^3 density, and a

confinement time of 20ms. This easily satisfies Lawson's Criteria and would result in a

full burn of the fusion fuel. 100 keV plasma temperatures would also be sufficient to all but eliminate D-D reactions (in a D-^{3}He fuel droplet), since the D-D cross section is miniscule compared to the D-^{3}He cross-section at those temperatures.

Figure 4. Strongly nested 600kV Potential Well to Compress Fusion Fuel. [8]

Otherwise, the D-D reactions would produce a damaging flux of neutrons. With 10^{11} antiprotons in the reaction area this process could happen 50 times before the Penning trap would have to be reloaded. If reloading time is made comparable to confinement time, this process would result in an approximately 0.75 MW of nearly continuous power in the form of protons and alpha particles. [8] The charged particles could then be directed by a magnetic nozzle, or transferred to a propellant to produce thrust. Currently, the Penn State group is designing a chamber, which could allow the charged particle energy to be transferred to a hydrogen propellant.

There are some obvious problems with the AIM confinement scheme. First, the $6x10^{17}$ ions/cm^3 density exceeds space charge limits. At the densities and temperatures proposed the by this concept the kinetic energies of the ions will exceed the energy of the

confining magnetic field. Another way of stating this is the kinetic pressure of the plasma will exceed the magnetic pressure. This situation causes a proven plasma instability that would shorten the confinement time (τ). Unless this instability is mitigated, confinement times are more likely to be on the order of microseconds.[11] In this case the nτ would fall one or two orders of magnitude short of satisfying Lawson's Criterion. It has been proposed by Ordonez [8] to mitigate this instability by dynamic injection and manipulation of electrons in the ion cloud. This concept proposes to re-circulate the mobile (compared to ions) electrons into and out of the central potential well where the ions are confined.[8] Extensive research to find the electric field, and re-circulation frequencies needed will be necessary. Also, the application of a 600 kV potential within such a small distance and time scale raises questions of breakdown and stability that would have to be answered. Operating high voltage electronics at the pulsed nanosecond timescale has been achieved with ICF lasers. Therefore, current technology could possibly be implemented to support this regime of operation. It is unknown whether the fission process at the initial stages to the AIM process will result in complete absorption of energy into the fuel droplet. Most likely, much of the fission product energy produced along the outer layer of the fuel droplet will escape the fuel. A more exact calculation should account for some loss of fission energy. Also, the fission product energy deposited in the fuel droplet is assumed to be a stable procedure, when in fact this is essentially a small fission bomb. It would be presumptuous to assume that this will not produce any instabilities.[11] Finally, as with most plasma research unexpected plasma instabilities will most probably arise that will limit the confinement time.

Assuming that the challenges facing full fusion ignition are overcome, one can speculate about the potential of the AIM propulsion engine. The rocket equation is a basic tool for estimating spaceflight parameters. The equation can be obtained by simply applying conservation of momentum to the rocket's motion and its exhaust. A relativistic version of the rocket equation can is shown below.[12]

$$\frac{\Delta V}{c} = \frac{R^{\frac{2Ve}{c}} - 1}{R^{\frac{2Ve}{c}} + 1}$$

Where R is the ratio of initial spacecraft mass, to final mass after propellant has been exhausted. The rocket engine produces a force for a time period to change the velocity of a certain mass in the amount ΔV. The exhaust velocity (Ve) is proportional to the specific impulse of a rocket, Isp, which is the thrust per unit mass flow rate of propellant. Often the Isp of a spacecraft is quoted rather than the exhaust velocity. This and other more detailed rocket equations can be manipulated in many different ways in order to characterize missions and propulsion schemes. A recent broad analysis of various propulsion options for many missions has been done. [12]   In this analysis the ΔV propulsion parameter was generally analyzed for missions ranging from solar system to fast interstellar travel. Table 1 shows some general ΔV's necessary for various missions.

Missions ranging in distance from 100-10,000 astronomical units (AU) are typically called interstellar precursor missions. This is because some believe that unique characteristics of the interstellar wind at approximately 80 AU severely limit earth-based investigation of cosmic particles and magnetic fields.[8]

Mission	Description	Typical ΔV (km/s)
Planetary	Deep space robotic missions throughout solar system	10
Omniplanetary	Ambitions human exploration throughout solar system	30-200
100-1000 AU	Interstellar Precursor Missions to the Heliopause (100AU) and the Gravity Lens focus (550 AU)	100
10,000 AU	Interstellar precursor mission to Oort Cloud	1000
Slow interstellar	4.5 light years in 40 yrs	30,000 = 0.1c
Fast interstellar	4.5 light years in 10 yrs or 40 light years in 100 yrs	120,000=0.4c

Table 1. Delta V's necessary for Various Missions. [12]

Furthermore, unknowns about the interstellar medium at 10,000 AU called the Oort cloud

could hold the key to unlocking secrets about the sun's formation, the mass of the solar

system, and other astronomical unknowns. [8]   Unmanned precursor missions to these

distances will answer questions that would provide useful information for manned

interstellar missions.

Using the rocket equation, designers of propulsion systems can estimate the

potential ΔV of a system by estimating the specific impulse (Isp), and the structure,

payload, and propellant mass. Kevin Kramer, et al.[8], at Penn State University Physics

department have estimated the performance of a small spacecraft (AIMstar) they designed in reference to a D-^{3}He, or D-T burning AIM engine for an unmanned 50 year trip to the Oort Cloud at 10,000 AU. The design includes a 100kg payload of equipment used to probe the interstellar medium and send information back to earth. The spacecraft has a dry mass of 361 kg and 1444 kg of propellant. Futuristic, high efficiency RTG's called AMTEC's are assumed to be in use for a 780 W power source needed for the scientific diagnostics and the data sending apparatus. A booster rocket containing the AIM engine is used to accelerate the spacecraft to a velocity of $\approx 0.003c$, then separated itself from the payload. The separation is necessary for communications with earth. The estimates for various spaceflight performance parameters are given in table 2. The ΔV is estimated to be 956 km/s which, according to table 1, does qualify the spacecraft for a trip to 10,000 AU. However, an assumption of 100% energy transfer between fusion products and propellant was made for these calculations. Therefore, these numbers are optimistic. Assuming that a lightweight energy transfer mechanism/structure is engineered, a near 100% energy transfer of proton and alpha particles from D-^{3}He fusion to a propellant is probably a reasonable assumption due to the relatively short range of charged particles in most materials. 100% energy transfer of D-T produced neutrons is an extremely unrealistic assumption without a severe mass penalty. With a dry mass of 361kg (for both fuels) it appears that no mass penalty has been assessed for energy transfer to propellant, or shielding of electronics for the D-T case. Also of significance is the amount of antimatter requirements. The D-^{3}He case is estimated to require less than 30μg of antiprotons. Antiproton production will be discussed shortly, where it will be seen that 30 μg of antiprotons is a realistic production possibility.

Parameter	D-T	D-^{3}He
ΔV	956	956
Ve (m/s)	5.98 x 10^5	5.98 x 10^5
Isp (seconds)	61,000	61,000
Power (MW)	33	0.75
Specific Power (kW/kg)	30.5	0.69
Antiproton Mass (μg)	130	28.5

Table 2. Estimated Performance of AIMstar Spacecraft design. [8]

Scientists at the NASA Marshall Space Flight Center, in collaboration with Penn State

have done a similar, but more general analysis of AIM based spacecraft potential. Also

using a detailed rocket equation analysis and estimations of Isp and structural ratios

(mass structure/mass propellant), they have estimated antimatter requirements as a

function of ΔV. This was done for missions of various payload requirements and the

results are displayed in figure 5.

Figure 5. Antiproton Requirements as a function of Delta V. [12]

Missions with 10-100 mT of payload, which could possibly be manned, are estimated to need anywhere between 2 -1000µg of antiprotons for various qualities of solar system travel. [12]   Structural ratios used in this analysis are unknown, but the ratio used (along with estimated Isp) limit this concept to a maximum of 10,000 AU space travel.

Annihilating grams of antimatter presents impressive comparisons with other reactions. However, the topic of obtaining a gram of antimatter is not as amusing. Currently, high energy proton synchrotron accelerators are used to produce antiprotons, although they were not built specifically for this purpose. These accelerators create high energy proton beams that are directed into a high Z target. The resulting collisions produce proton-antiproton pairs as well as other numerous particles. Accumulator storage rings are used to collect the antiprotons produced.   Currently, there are two laboratories in the world that have accelerators with capabilities to produce controlled antiprotons: CERN in Geneva, Switzerland, and FNAL (Fermi National Accelerator Laboratory) in Batavia, Illinois. FNAL is currently capable of producing, at full capacity operation, approximately 14 ng of antiprotons per year.[4]   This method of producing antiprotons is an extremely inefficient and expensive process. In the ideal case, the efficiency is limited to 1/2 because you must create a proton for every antiproton. Assuming a reasonable antiproton production frequency of 1 per 10^5 proton-target collisions with 120 GeV protons, the current efficiency in producing antimatter has been estimated by Schmidt, et al to be $4x10^{-8}$.[12]   At this efficiency and 10 cents/kw-hr energy supply, the cost to produce antiprotons is currently around 62.5 trillion/gram.   At FNAL there are plans for improving this efficiency. A new recycler ring that will store

antiprotons that would otherwise be lost should increase the capacity to 140 ng/yr. [4]

Currently, CERN operates a facility called the Antiproton Decelerator (AD). This facility

has the capability to produce, collect, cool, and decelerate antiprotons at a maximum

capacity of 15 picograms. [12] It has been estimated by the Rand Corporation that a

facility dedicated to antiproton production costing 3-10 billion dollars could produce 0.1-

1gram of antiprotons per year. As discussed earlier, for various manned flights within the

solar system and small-unmanned mission to the Oort Cloud antiproton needs could

range between 2 and 1000 micrograms of antiprotons. Figures 6 and 7 summarize the

relationship between production capabilities, antiproton needs, and costs.

Antiproton Production (per year) and estimated AIM antiproton Requirements
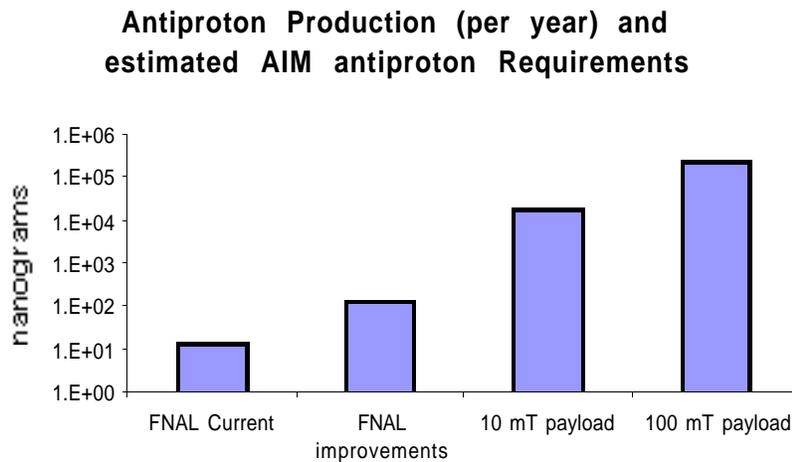
Figure 6. Antiproton production capabilities (per year) and sample of AIM
antiproton requirements for ambitious manned solar system travel.

Antiproton Costs vs. AIM Needs
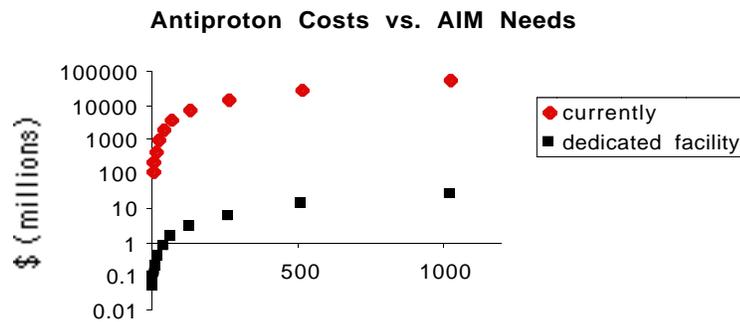
Figure 7. Antiprotons costs for Current FNAL Facilities and for a newly built
dedicated facility.

Figures 6 and 7 show that to facilitate a serious attempt at AIM propulsion a dedicated,

more efficient antiproton facility must be built. With current capabilities the smallest of

antiproton requirements would cost over a billion dollars and take over a 1000 years to

produce the antiprotons. Even if new technology came available to dramatically increase

the efficiency of the current facilities, running a full time operation would mean new

facilities would have to be built for high energy physics research.   Therefore, any

imaginable possibility includes the construction of high dollar facilities.

Realizing that production of antiprotons is the first step, the logical second step is

devising a method of collecting and preserving the antiprotons. The antiproton's charge

and mass characteristics allows the possibility of identifying, and magnetically

controlling the particle's motion. This control allows for the separation of antiprotons

from the rest of particles produced in the collision. Once isolated, Penning traps are a

possible method of storing them. In order to make a cost-efficient, portable Penning trap

the energy of the antiprotons must be degraded from its initial post-creation energy.

Otherwise, enormous magnets would be necessary eliminating any chance of being easily

transported. Currently, CERN has a Low Energy Antiproton Ring (LEAR) that is

capable of reducing an antiproton's energy to 5.9 MeV.   A similar ring could be built at

FNAL at a cost of approximately 10 million dollars.[12] Other relatively inexpensive

antiproton decelerators are being developed for lower capacity production. Synergistic

Technologies of Los Alamos is developing a magnetic degrading spectrometer that

simply and inexpensively delivers decelerated antiprotons.[12]   This design will have

production capacity of much less than 1 ug, however, it could produce enough

antiprotons for the demonstration AIM physics. Once, you have a low energy antiproton

beam, such as available at LEAR, it is possible to inject the beam into a Penning trap.

Penning traps have been successfully demonstrated to confine charged particles

for various amounts of time. At the University of Washington, a Penning trap confined a

positron (anti-electron) for over a month.[3] In 1986 a penning trap successfully confined

as many as 200 antiprotons received from a 150 nsec pulse of antiprotons from LEAR.

The antiproton energy was degraded to approximately 1 KeV by a thick Aluminum foil,

then trapped for a period of 100 sec, after which they were allowed to escape so detection

could allow for proof of the entrapment.[3]   Since that time, some serious attempts have

been made at trapping antiprotons. Michael Holzsheiter, a physicist at Los Alamos

National Laboratory, headed an effort that built an antiproton trap called the "catcher

trap". This device lowers the energy of an energetic antiproton beam to 10-30 keV by

passing it through a SF_6 gas cell and an Al foil. The resulting beam is then directed into a

Penning trap-type structure to confine the antiprotons. This "catcher trap" has

demonstrated the ability to trap 10^6 antiprotons for several hours from a 250 nsec

antiproton beam pulse. [7]   If the confined antiprotons could be cooled, then this would

allow subsequent pulses to add antiprotons to the already confined group of antiprotons.

Cooling has been achieved by Holzsheiter, et al., by injecting electrons into the trap.

Electrons suffer collisions with the antiprotons, accepting their energy and then radiating

in the form of synchrotron radiation as they spin around the magnetic field. [7]   Thus, with

10 consecutive beam pulses, 10^7 antiprotons could be confined. Another important

implication of antiproton cooling is that Holzsheiter's group found evidence that the

annihilation cross-section with vacuum impurities decreases dramatically as antiprotons

are cooled.[6]   This could reduce the quality of vacuum necessary, therefore reducing trap

costs. This catcher trap technology shows potential in regards to trapping, however, it is

not a lightweight portable trap. At Penn State an antimatter group led by physicist Gerald

Smith have tested a small, portable Penning trap designed to confine 10^9 antiprotons for

4-10 days. [4]   Operating at 4K, the trap is designed to accept antiprotons cooled to 10 eV

energies by the "catcher trap" decribed earlier. [14]   The device is 100cm tall, 30 cm in

diameter and 55 kg fully loaded. [7]   Permanent SmCo magnets provide an axial magnetic

field of 0.5 T. This size of magnetic field limits the storage density, by Charge density

limit, to 10^9/cm^3. [10]   With trapping area of 10cm^3, the device is theoretically capable of

trapping 10^{10} antiprotons. This is a prototype for slightly larger Penning trap theoretically

capable of 10^{14} antiprotons stored for 120 days. With this capability, 1000 such traps

lifted to space would produce approximately 140 ng of usable antiprotons for travel

within the solar system. [4]   To transport larger amounts to space, more traps or larger

magnetic fields will be needed. Both of these options have their practical limits. Too

many traps would be much to massive to launch into space, and there are also limits on

the possible magnitude of magnetic fields available. Even with larger magnetic and electric field, the Coulomb force prevents Penning traps from achieving densities needed for the transport of micrograms and more. Therefore, for more ambitious missions needing larger amounts of antimatter an alternative trapping method must be conceived. One idea involves the production of antihydrogen.

The presence of antihydrogen atoms has been detected. Experiments at CERN have been conducted in which 11 antihydrogen atoms were produced and detected.[1] To produce the antihydrogen, an antiproton beam was directed into a target. The antiprotons interact with Coulomb field of a nucleus to produce gamma ray photons. These photons then interact with the nucleus themselves to create an electron-positron pair. Occasionally, an antiproton captures a positron forming a fast moving antihydrogen atom. This does prove that antihydrogen can exist, however, this is not an efficient means of producing the exotic atoms and definitely not a trapping possibility. It has been proposed that antihydrogen atoms could be created by injecting positrons and antiprotons into a nested double well potential barrier configuration similar to the trap described earlier. This will need to be done at extremely low temperatures ($<1^0$K) as recombination goes as $1/T^5$. If synthesis this is achieved, then antihydrogen confinement can be done with Pritchard-Ioffe traps, a technology already existing in labs experimenting with atomic hydrogen. Labs have achieved confinement of $10^{14}/cm^3$ using the interaction between the atomic magnetic moment and an inhomogeneous magnetic field. [4] Some claim that this technology has the potential for trap densities reaching 10^{17}/cc, or 0.166 ug/cc. But, as densities approach 10^{14} /cc instabilities exist. At these densities interatomic scattering causes positron "spin flip", after which the trap caused these atoms

to be ejected from the trap rather that confined. Ultimately, to achieve storage on the microgram scale, the transition to liquid or solid antihydrogen will be needed. To achieve the transition to the liquid phase micro-Kelvin temperatures will be necessary which could possibly be achieved by laser cooling or residual gas cooling. [7] Residual gas cooling is a possibility only if the suspicion that annihilation is retarded at extreme low temperatures is confirmed.[7] Like hydrogen, liquid and solid antihydrogen is expected to be diamagnetic. If this is the case, then the liquid could be confined with levitation techniques using magnetic fields.[7] If the antihydrogen could be condensed to liquid or solid form then densities approaching 10^{23} atoms/cm^3 could be achieved. In this case, 140ng of antihydrogen would occupy a volume of less than 1.2×10^{-8} m^3. If the solid form could be achieved, then stability would have to be closely examined. Any annihilation on the surface of the liquid or crystal could cause sputtering from the wall of the confining apparatus. [13] The sputtered matter could in turn produce more annihilation resulting in an uncontrolled chain reaction. [4] Soon, a facility at CERN called the antiproton decelerator will have the capability to produce, collect, cool, and decelerate antiprotons. The facilities main purpose will be to research antihydrogen production as well as provide low energy antiprotons for trapping experiments.

Safety from radiation is another topic that must be addressed when considering space travel. Both manned and unmanned missions involve radiation shielding considerations. While electronics are much more susceptible to radiation that humans, they still have exposure limits which necessitate shielding for unmanned missions. An AIM engine running with D-T fuel will have the approximately the same radiation shielding requirements as any other fusion scheme. But, an AIM engine operating with

D-^{3}He as fuel will have additional shielding requirements compared to most other fusion

propulsion methods. This is due to the payload of antiprotons necessary and the potential

radiation hazard that is associated with them. If a fuel payload of 100 µg of antiprotons

were to suddenly annihilate with its confinement structure there would be a nearly

instantaneous flux of 4.2 x 10^{20} gamma rays. 57% of those gamma rays would have an

energy of approximately 200 MeV, while the others would be 0.511 MeV gammas. The

gamma rays account for only 43% of the energy released from the annihilation. The rest

is released in the form of neutrinos. Neutrinos interact very little with matter, therefore

the gamma flux accounts for the vast majority of the radiation risk. This potential

radiation hazard adds much unwanted mass to the system design and may offset the

lightweight advantages originally assumed. Another risk involves the regulation and

supervision of antimatter fuel for fear that one would use antiprotons as a weapon of

mass destruction. However, the fact that all end products of proton-antiproton

annihilation are all neutral forms of radiation make it a poor choice of weaponry.

In conclusion, the AIM concept is not much different from other fusion concepts.

Like other concepts, plasma instabilities exist that must be overcome in order to achieve a

full fusion burn. The D-^{3}He AIMstar design estimates approximately 1 kW/kg specific

power, and many other fusion concepts propose similar specific powers if not higher.

The specific power for AIM systems would in reality have a lower specific power when

shielding mass is added for safety considerations. This shielding mass could offset the

advantage of using antimatter for a lightweight driver. For AIM propulsion systems to

exist new facilities would have to be built for dedicated antiproton and liquid

antihydrogen production. However, current antiproton production is ample to test the

physics of this concept, which could prove useful for developing alternative antimatter

driven fusion concepts. Further development of this type of concept could be competitive

in a fusion field that has struggled to achieve full burn of fusion fuels.

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