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Antimatter Requirements and Energy Costs for Near-Term Propulsion Applications

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The superior energy density of antimatter annihilation has often been pointed to as the ultimate source of energy for propulsion. However, the limited capacity and very low efficiency of present-day antiproton production methods suggest that antimatter may be too costly to consider for near-term propulsion applications. We address this issue by assessing the antimatter requirements for six different types of propulsion concepts, including two in which antiprotons are used to drive energy release from combined fission/fusion. These requirements are compared against the capacity of both the current antimatter production infrastructure and the improved capabilities that could exist within the early part of next century. Results show that although it may be impractical to consider systems that rely on antimatter as the sole source of propulsive energy, the requirements for propulsion based on antimatter-assisted fission/fusion do fall within projected near-term production capabilities. In fact, a new facility designed solely for antiproton production but based on existing technology could feasibly support interstellar precursor missions and omniplanetary spaceflight with antimatter costs ranging up to \$6.4 × 10⁶ per mission.

Nomenclature

c = speed of light
E_{fusion} = energy contribution from fusion
E_{in} = energy into antiproton production process
E_{out} = antimatter rest mass energy out of production process
$E_{\bar{p}p}$ = energy contribution from antimatter annihilation
I_{sp} = specific impulse
K = total energy cost
k_{grid} = power utility cost (\$ per unit energy)
M_a = mass of antiprotons
M_p = propellant mass
M_{pay} = payload mass
M_0 = vehicle dry mass (structure plus payload)
R = spacecraft wet mass to dry mass ratio
V_e = rocket exhaust velocity
β = fusion energy to annihilation energy ratio
γ = Lorentz–Fitzgerald factor, $\{1/\sqrt{[1-(V_e/c)^2]}\}$
ΔV = mission velocity requirement
η_{conv} = energy conversion efficiency
η_{grid} = wall-plug efficiency
η_{tot} = total production efficiency
η_e = propulsion energy utilization efficiency
λ = vehicle structure to propellant mass ratio

Introduction

THE annihilation of subatomic particles with their antimatter counterparts has the highest energy per unit mass of any reaction known in physics. The energy released from proton–antiproton annihilation (1.8×10^{14} J/g of antiprotons) is 10^{10} times greater than oxygen–hydrogen combustion and at least 100 times more energetic than fission or fusion. One gram of antihydrogen, a mirror hydrogen atom composed of an antiproton and positron, reacted with the same amount of normal hydrogen produces a total energy equivalent to that delivered by 23 Shuttle external tanks (ET).

Since 1953 when Eugene Sanger first proposed use of electron–positron annihilation to produce thrust,[1] there have been many attempts[2–6] to identify ways of exploiting antimatter for propulsion. Practically all of these concepts involve applying the products from proton–antiproton annihilation either to create thrust directly or to energize a propellant through interparticle collisions or heating of an intermediate solid core. In addition, the scientific community, which until several decades ago exhibited only casual interest in the subject, is now devoting more attention and resources to uses of antimatter. The best examples of this are the accelerators at Fermi National Accelerator Laboratory (FNAL) and the European Laboratory for Particle Physics (CERN), which routinely produce antiprotons to extend the energy range of particle collision experiments.

Although the worldwide production capacity has been growing at a nearly geometric rate since the discovery of the antiproton in 1955, the current output rate of 1–10 ng per year is minuscule compared to that of other exotic materials. For this reason, some people have questioned the practicality of using antimatter for propulsion, at least within the next century or so. They feel that the energy costs would be exorbitantly high and would never allow antimatter to be competitive with other propulsion technologies.

Most of this skepticism stems from the misconception that all of the concepts that utilize antimatter rely on the annihilation reaction as the sole source of propulsive energy. Although it is true that conventional antimatter systems, which derive all their energy from annihilation, offer the highest specific impulse ($I_{\mathrm{sp}} \sim 10^5$–$10^7$ s) of any propellant-based propulsion concept, there are several antiproton-driven hybrid fission/fusion concepts that require far less antimatter, while still coming close to the performance of conventional antimatter rockets ($I_{\mathrm{sp}} \sim 10^4$–$10^6$ s) (Refs. 7–10). In fact, the quantities required to test and demonstrate these concepts may be well within the range of existing production facilities at FNAL and CERN, once several promising upgrades are incorporated.

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It appears that the prospects of exploiting antimatter for space propulsion are not so bleak after all and may indeed be quite favorable. We have confirmed this by conducting a study in which we calculated the antimatter quantities required to accomplish a broad range of missions and compared these values against the production costs of the current infrastructure. Using these numbers as a reference, we examined the incorporation of upgrades and improvements that could further increase production capacity and ultimately lower energy costs. The results suggest an evolution of production infrastructure, starting with quantities to support development of antimatter-assisted fission/fusion propulsion technology, followed by actual use of these systems for omniplanetary spaceflight and interstellar precursor missions beyond the heliopause.[11]

Fundamental Energy Cost Constraints

The creation of antimatter is an inherently energy-intensive process. Not only must energy be converted into rest mass of antiparticles, but the application of this energy is ordinarily inefficient and potentially quite expensive. The energy cost can be generally expressed as

$$K = k_{\text{grid}} E_{\text{grid}} \tag{1}$$

where k_{grid} is the unit cost of energy and E_{grid} is the energy consumed at the wall plug, that is, off the commercial power grid.

The wall-plug energy E_{grid} is related to the antimatter rest mass collected M_a and the overall efficiency of converting wall-plug power into antimatter η_{tot} by

$$E_{\text{grid}} = M_a c^2 \big/ \eta_{\text{tot}} \tag{2}$$

The efficiency η_{tot} may be separated into two parts; that is,

$$\eta_{\text{tot}} = \eta_{\text{conv}} \eta_{\text{grid}} \tag{3}$$

where η_{conv} is defined solely by features of the production and collection process and η_{grid} is the electrical efficiency of the accelerator system. Conservation of baryon number requires that formation of an antiparticle is always accompanied by creation of its standard particle counterpart. Thus, the antiproton can at most be one-half of the total rest mass produced in a perfectly efficient conversion process. This sets a theoretical limit on η_{conv} of $\frac{1}{2}$ (Ref. 12).

The total energy cost is obtained by substituting Eqs. (2) and (3) into Eq. (1); that is,

$$K = \frac{k_{\text{grid}} M_a c^2}{\eta_{\text{conv}} \eta_{\text{grid}}} \tag{4}$$

Equation (4) clearly shows that η_{conv} and η_{grid} are major factors in dictating energy costs. Unfortunately, the values associated with present-day production facilities, particularly η_{conv}, are extremely low. A good example of this is FNAL, which creates antiprotons by means of colliding beams of relativistic protons with high-atomic-number (high-Z) material targets. The protons, which are typically accelerated to energies of 120 GeV (120×10^9 eV), yield a spray of particles at the collision site. Electrons, positrons, and pions are the most copious products, whereas proton–antiproton pairs are relatively rare due to their large mass. Furthermore, only a small portion of the antiprotons leave the target at the proper momentum and small enough exit angle to be magnetically focused and cooled for subsequent storage.

The performance of the overall collection process is quite low and yields about 1 antiproton per 10^5 proton collisions. Multiplying acceleration energy (120 GeV/proton) by collection ratio (10^5 proton/antiproton) yields an energy requirement of 1.2×10^{16} eV/antiproton or 1.16×10^{21} J/g. Dividing this into the specific rest mass energy c^2 yields $\eta_{\text{conv}} = 7.8 \times 10^{-8}$. Furthermore, FNAL facilities consume 14 MW of power to deliver 5×10^{12} 120-GeV antiprotons every 1.5 s onto the production target (J. Marriner, private communication). This equates to $\eta_{\text{grid}} = 5 \times 10^{-3}$ and, according to Eq. (3), translates to $\eta_{\text{tot}} = 3.9 \times 10^{-10}$. Substituting these values and an assumed k_{grid} of \$0.10/kW-h into Eq. (4) yields an energy cost of $\$6.4 \times 10^{15}$ per gram of antiprotons.

Obviously, the cost of producing large quantities of antimatter, that is, gram scale or greater, with current facilities is excessively high. However, studies have shown that the efficiency of production based on proton/high-Z material collisions can be improved substantially by optimizing proton acceleration energy and duty factor and by incorporating improved collection methods.[13,14] It is also reasonable to assume that the energy utilization of a dedicated antiproton production facility could be made more efficient, at least to a level comparable to other new accelerator systems, thus yielding $\eta_{\text{grid}} \sim 10\%$. [Accelerator production of tritium, under development at the Los Alamos National Laboratory would provide, if completed, 100 mA of protons at 1.6-GeV energy on target with a wall-plug efficiency of 42%. The value of 42% may not be verified because the Department of Energy has recently decided to use commercial power reactors to make tritium (S. Howe and G. Lawrence, private communication).]

For example, assuming a collection ratio of 1 antiproton per 20 collisions[15,16] and a 10% wall-plug efficiency yields an η_{tot} of 3.9×10^{-5}. This five order of magnitude improvement over current capability yields a cost of $\$6.4 \times 10^{10}$ per gram, which is roughly 10,000 times the cost of an equivalent energy load of Shuttle ET propellants. Such improvements would most likely require a substantial investment of $\$3\text{–}10 \times 10^9$ for a dedicated production facility.[13,14]

It appears that as long as commercial power rates remain near current levels of \$0.01–\$0.1/kW-h, the cost of producing large quantities of antimatter will be high, regardless of the extent to which efficiency can be improved. For large-scale production to become even remotely practical (especially at the kilogram to metric ton quantities envisioned for interstellar missions using pure antimatter rockets), power utility costs will have to drop dramatically below current levels ($k_{\text{grid}} \ll \$0.1$/kW-h). This is unlikely to occur until abundant power based on a conceivably free resource becomes available.

The prospects for applications involving small amounts of antimatter ($M_a \sim 1\ \mu$g), however, look much more promising. Several near-term technologies being pursued in the areas of commercial radioisotope medicines: diagnostic tomography and cancer therapy require antimatter quantities ranging from only 0.1–100 ng (Ref. 17). With today's production infrastructure, the energy costs for these applications lie within the range of $\$6.4 \times 10^5$–$\$6.4 \times 10^8$.

What is more important, especially for high-energy applications such as propulsion, is the significant reduction in antimatter energy costs that could be achieved by incorporating several upgrades into FNAL and other existing facilities. As the following discussion shows, a two–three order of magnitude reduction in energy costs appears feasible and could be implemented within the next decade. Also, by incorporating existing technologies into design of a dedicated antiproton production facility, the 1–100 μg quantities required for omniplanetary spaceflight and interstellar precursor missions based on antimatter-assisted fission/fusion would cost $\$6.4 \times 10^4$–$\$6.4 \times 10^6$.

Antimatter Propulsion Concepts

Approximately two-thirds of the total rest mass energy of an annihilating proton–antiproton pair goes into the immediate production of charged particles. It is important to utilize the energy of these products as soon as possible after the annihilation event, before they successively decay into neutral gamma rays and unusable neutrinos. This entails 1) heating a propellant directly through particle/fluid collisions, or 2) absorbing particle energy in an intermediate material that heats a propellant, or 3) directing the highly energetic charged pions or muons out a magnetic nozzle to produce thrust. We consider six different antimatter propulsion concepts. These include four conventional systems driven solely by annihilation energy and two hybrid systems powered by antimatter-assisted fission/fusion.

The simplest conventional system is the solid-core concept[5,18] that uses antiprotons to heat a solid, high-Z, refractory metal core. Propellant is pumped into the hot core and expanded through a nozzle to generate thrust. The performance of this concept is roughly equivalent to that of the nuclear thermal rocket ($I_{sp} \sim 10^3$ s) due to temperature limitations of the solid (~3500 K). However, the antimatter energy conversion and heating efficiencies are typically high due to the short mean path between collisions with core atoms ($\eta_e \sim 85\%$).

A slightly more sophisticated concept is the gaseous core[5,6,18] that substitutes the low-melting-point solid with a high-temperature gas, thus permitting higher operating temperatures and performance ($I_{sp} \sim 2 \times 10^3$ s). However, the longer mean free path for thermalization and absorption results in much lower energy conversion efficiencies ($\eta_e \leq 35\%$).

The third conventional concept is the plasma core,[6,18] where the gas is allowed to ionize and operate at even higher effective temperatures. Heat loss is suppressed by magnetic confinement in the reaction chamber and nozzle. Although performance is extremely high ($I_{sp} \sim 10^4$–10^5 s), the long mean free path results in very low-energy utilization ($\eta_e \leq 10\%$).

The ultimate conventional concept is the beamed core,[3,6,11] which avoids the problems of heating a secondary fluid altogether. Here, the charged products of the proton–antiproton annihilation are directly expelled out of the vehicle along an axial magnetic field. The exhaust velocities of these products are exceptionally high ($I_{sp} \sim 10^7$ s), approaching the speed of light. Although energy utilization efficiencies are also high ($\eta_e \sim 60\%$), the flow rate and thrusts are typically very low.

The hybrid antimatter/fusion concepts differ from the conventional systems in that antiprotons are used as a driver to initiate a combined fission/fusion process in a compressed plasma or condensed material target. Practically all of the propulsive energy is derived from fusion reactions. Consequently, antimatter requirements are much lower than the pure-antimatter systems.

The first of such processes is antimatter-catalyzed microfission/fusion (ACMF).[7,8] Here, a pellet of Deuterium–Tritium (D–T) and U-238 is compressed with particle beams and irradiated with a low-intensity beam of antiprotons. The antiprotons are readily absorbed by the U-238 and initiate a hyperneutronic fission process that rapidly heats and ignites the D–T core. The heated fission and fusion products expand to produce thrust, but the inherent isotropy of the flow results in a lower effective energy utilization and jet efficiency. Although additional thrust is obtained from an ablating surface that absorbs neutrons and electromagnetic radiation from the ignited pellet, the performance of this concept is lower than the plasma and beamed-core rockets ($I_{sp} \approx 13{,}500$ s). Gaidos et al.[7,8] have shown that the interaction between the antiproton beam and target exhibits extremely high-gain yielding a ratio of fusion energy to antimatter rest mass energy β of 1.6×10^7. However, energy utilization is also lower due to the isotropic expansion process ($\eta_e \sim 15\%$). Assuming a three order of magnitude improvement in the efficiency of producing antiprotons over current values, the net energy gain is 640.

Another concept is antimatter-initiated microfusion (AIM).[9] Here, an antiproton plasma within a special Penning trap is repetitively compressed via combined electric and magnetic fields. Droplets containing D–T or Deuterium–Helium3 (D–He3) mixed with a small concentration of a metal, such as Pb-208 or U-238, are synchronously injected into the plasma. The main mechanism for heating the liquid droplet is antimatter-induced fission fragments that have a range of 45 μm in the droplet. The power density released by the fission fragments into the D–T or D–He3 is about 5×10^{13} W/cm^3, which is enough to completely ionize and heat the fuel atoms to fusion ignition. The heated products are directed out magnetic field lines to produce thrust. The I_{sp} and energy efficiency for this concept are higher than ACMF ($I_{sp} \approx 67{,}000$ s and $\eta_e \sim 84\%$ with D–He3, and $I_{sp} \approx 61{,}000$ s and $\eta_e \sim 69\%$ with D–T). The gains β are 10^5 for D–He3 and 2.2×10^4 for D–T (Ref. 9). Again assuming a three order of magnitude improvement in antiproton production efficiency, these gains are near breakeven in terms of net energy flow.

Although net energy gain is a fundamental consideration in the development of terrestrial fusion power systems, it should not be the case for in-space power sources designed for propulsion. For such applications, the mass and portability of the source are equally important to energy gain. This is where antiproton-assisted fission/fusion offers a distinct advantage over conventional fusion-based propulsion concepts.

Antimatter Requirements

We consider six reference missions that reflect ambitious robotic and crewed exploration of the solar system, precursor interstellar study of phenomena outside the heliopause, and missions to our closest stellar neighbors. These reflect the data used in a recent evaluation of propulsion options for interstellar missions.[11] The missions and their associated ΔV are shown in Table 1.

Our goal is to calculate the antimatter quantities for each of the earlier described concepts as a function of mission requirements, more specifically ΔV and payload mass M_{pay}. We begin by taking the definition of mass ratio, $R = (M_p + M_0)/M_0$ and equating it to the expression for R from the relativistic rocket equation.[19] This yields the following relationship for propellant-to-dry-mass ratio:

$$M_p/M_0 = R - 1 \tag{5}$$

where

$$R = \left[\frac{1 + \Delta V/c}{1 - \Delta V/c}\right]^{c/2V_e} \tag{6}$$

Note that M_p includes both antimatter and propellant and that M_0 accounts for vehicle structure, systems, and payload. The fraction of antimatter making up the total propellant requirement is determined by equating the actual energy introduced into the propellant with the jet energy of the exhaust; that is,

$$(E_{\bar{p}p} + E_{\text{fusion}})\eta_e = [M_p - (E_{\bar{p}p} + E_{\text{fusion}})/c^2]c^2(\gamma - 1) \tag{7}$$

The left-hand side of Eq. (7) represents the combined annihilation and fusion energy applied to the exhaust and accounts for the energy-utilization efficiency of the nuclear products. The right-hand side of Eq. (7) represents kinetic energy of the exhaust products, where the rest mass of the annihilation and fusion energy is subtracted from the total reaction mass. $E_{\bar{p}p}$ is the rest mass energy of the annihilation reaction and accounts for both proton and antiproton reactants, $E_{\bar{p}p} = 2m_A c^2$. The fusion energy is expressed in terms of annihilation energy with $E_{\text{fusion}} = \beta E_{\bar{p}p}$.

Substituting the definitions of $E_{\bar{p}p}$ and E_{fusion} into Eq. (7) and rearranging terms yield an expression for the antimatter-to-propellant-mass ratio. This in turn can be multiplied by Eq. (5) to yield an expression for antimatter-to-inert-mass ratio as a function of mission requirements, propulsion performance, fusion gain, and energy efficiency:

$$\frac{M_a}{M_0} = \frac{1}{2(1 + \beta)}\left[\frac{\gamma - 1}{\eta_e + \gamma - 1}\right](R - 1) \tag{8}$$

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)

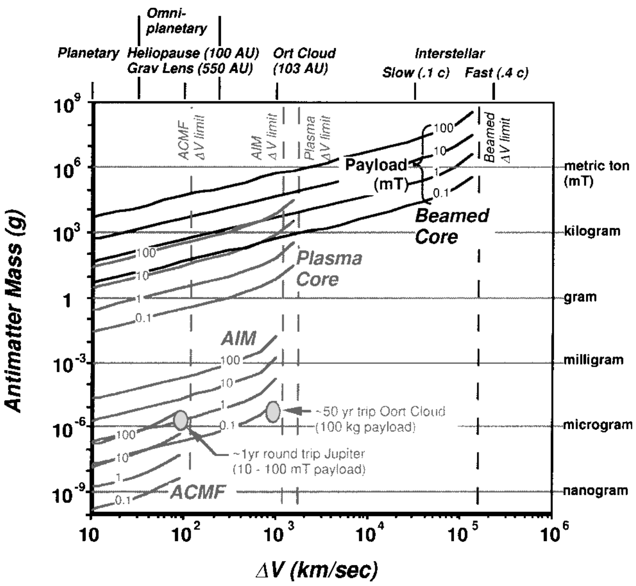

Fig. 1 Antimatter requirements for different propulsion concepts.

Inert mass can be expressed in terms of payload mass by using the definition for structure to propellant ratio, $\lambda = M_{\text{struct}}/M_{\text{prop}}$, where $M_{\text{struct}} = M_0 - M_{\text{pay}}$,

$$M_0 = [1/(1 + \lambda - \lambda R)]M_{\text{pay}} \tag{9}$$

Substituting Eq. (9) into Eq. (8) yields the following expression for M_a in terms of M_{pay} and propulsion/performance parameters:

$$M_a = \frac{1}{2(1+\beta)}\left(\frac{\gamma - 1}{\gamma + (\eta_e - 1)}\right)\left(\frac{R-1}{1+\lambda - R\lambda}\right)M_{\text{pay}} \tag{10}$$

We use Eq. (10) to illustrate in Fig. 1 the dependence of antimatter mass on payload and mission velocity[11] for the ACMF, AIM, plasma-core, and beamed-core concepts. Plots for the solid- and gas-core concepts are not shown because the I_{sp} are lower than either of the hybrid concepts and the antimatter requirements are only marginally less than that of the plasma core. For these calculations, values of λ were synthesized from estimates by various sources.[4–11,17] A λ value of 0.3 was assumed for both the solid- and gas-core concepts to account for tankage, structure, and reaction containment. The λ values for the plasma core, beamed core, and AIM were lower ($\lambda = 0.2$) because of the improved reaction confinement performance expected with these more advanced concepts. With the ACMF concept, a much higher λ of 0.7 was assumed to account for the large mass of the ion driver system.

In the lower range of mission velocities ($10 \leq \Delta V \leq 10^3$ km/s), the ACMF and AIM concepts are clearly superior in terms of minimizing antimatter requirements. For planetary, early interstellar precursor, and simple omniplanetary applications, ACMF exhibits the best performance. The reference case of a 1-year human round-trip mission to Jupiter with a 10–100 metric ton payload requires an antimatter quantity of 1–10 μg. It appears as though this requirement could drop into the 1–10 ng range for payloads consistent with uncrewed, planetary missions. However, ACMF was originally conceived for crewed omniplanetary flight and is probably not scaleable to smaller sizes due to the large mass of its ion driver system. Therefore, ACMF is restricted to missions that would require 1–10 μg and ΔV less than or equal to 100 km/s.

The AIM concept, which does not need a driver and benefits from a higher I_{sp}, can accomplish more ambitious missions, such as interstellar precursor trips to the Oort cloud. However, the antimatter requirement is roughly one to two orders of magnitude greater than ACMF. For that reason, this concept is better suited for uncrewed missions with smaller payloads. The design point in Fig. 1 represents a 50-year trip to the Oort cloud with a 100-kg payload. Even with the higher rate of antiproton usage, the total requirement is still relatively low, within the 10–100 μg range. The structural ratio and I_{sp} limit the maximum ΔV to 10^3 km/s.

The only antimatter concept that can achieve velocities above 2×10^3 km/s and accomplish missions well beyond solar influence is the beamed core. Although a structural ratio consistent with the AIM and plasma core concepts is assumed, the much higher exhaust velocity of the annihilation products permits vehicle accelerations to velocities approaching $0.4c$, which would enable fast missions to Alpha Centauri in 10 years.[11] At first this appears quite attractive until one notes that the antimatter requirement is many orders of magnitude greater than either the ACMF or the AIM reference case. For a payload of 1 metric ton, the antimatter requirement is about 40 metric tonnes, depending on the mission. The beamed core requires tremendous amounts of antimatter, but it is the only concept that can travel to the nearest stars (4–40 light years) within a reasonable time (10–100 years).

Although the inordinately high antimatter requirements of the conventional systems are impractical to consider in the near term, the more modest quantities associated with ACMF and AIM may be quite attainable. The catalyzed systems could not be used for trips to the stars, due to their limited ΔV of only 10^2–10^3 km/s. However, ACMF and AIM appear to have sufficient performance to propel interstellar precursor probes and support human exploration of the entire solar system.

Antimatter Production Capability

Almost all of the controlled antimatter in the world is produced at either CERN or FNAL. Figure 2 shows a schematic of the accelerator system currently used at FNAL for producing antiprotons.[20] Protons from an H^- source are sequentially accelerated to 120 GeV in the main injector. These protons then collide with a target, which produces antiprotons and a plethora of other fundamental particles. The antiprotons are sign selected with magnets and accumulated in the 8-GeV antiproton source. Here they are stochastically cooled and temporarily held within the storage ring. For physics experiments, these antiprotons are reinjected as intense beams back into the main ring to carry out collisions with protons at very high energies. For future space propulsion applications, the 8-GeV antiprotons could be loaded into a new ring (not shown) and decelerated to an energy low enough to allow collection in traps.

This unique capability was added from the late 1970s to the late 1990s to increase the energies of particle collision experiments. During a year-long period between 1997 and 1998, FNAL produced 1 ng of antiprotons. This was done in the midst of a very large experimental program that did not have sufficient funds to run 24 hours per day, 365 days per year. The instantaneous accumulation rates were around 10^{11} antiprotons/h, so a full year of operation would have produced 8.8×10^{14} antiprotons. This equates to an annual yield of approximately 1.5 ng, which is three to four orders of magnitude less than the quantities required for missions using ACMF and AIM.

Remember that neither of the facilities at FNAL or CERN was designed for the sole purpose of producing antiprotons. This capability, which was added after the facilities had been operating for some time, was only intended to generate enough antiprotons for collision

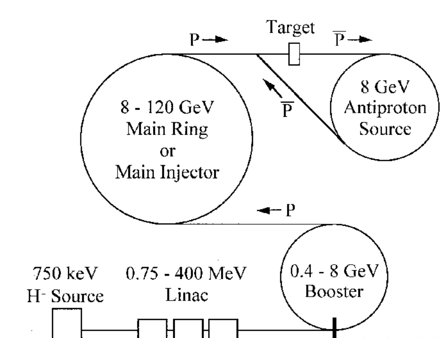

Fig. 2 Antiproton production facilities at FNAL.[20]

experiments. The collection ratio, which can be viewed as the effective antiproton yield, (antiprotons collected) per proton on target, was not the main concern. Although the current ratio of 10^{-5} is very low, there are ways in which it can be increased.

We consider the case of FNAL, which is the largest, most convenient source of antiprotons in the United States. From 1998 to mid-1999, FNAL's accelerator was down for commissioning of a new main injector. We expect that when the new injector comes on-line, production yields will increase by another order of magnitude. This will eventually boost the production rate to about 10^{12} antiprotons/h. We, therefore, expect that by the early part of next decade, the total annual production capacity should approach 15 ng. At the same time, FNAL could start incorporating even better collection devices and techniques. Development of more efficient collection equipment, such as improved focusing horns and multiple large-aperture receivers, has been considered,[13,14] and could culminate in substantial production gains. It is quite reasonable to expect perhaps an additional 50-fold increase in efficiency with these upgrades, thus yielding a 500-fold improvement over current capability.

The impact of incorporating such improvements is shown in Fig. 3. The final result is a nearly three order of magnitude increase of production capacity into the microgram range. This is significant because at this level one can seriously begin to consider use of antimatter-catalyzed fusion propulsion devices for space applications.

These production enhancements are obviously aimed at expanding support of scientific research at FNAL. However, customers who are planning to use the facility for replenishment of portable antiproton devices, such as NASA and commercial users, would require an additional feature beyond those planned to support scientific activities.

In the current production process, high-energy antiprotons from the original proton collision site can be stored temporarily in the main injector at a relatively low kinetic energy of 433 MeV. They are subsequently extracted and accelerated to much higher energies for collision experiments. To transfer these antiprotons into a small-volume, portable device, such as a Penning trap, an additional deceleration process that would reduce antiproton energies from 433 MeV to no more than 20 keV is required between the main injector and storage device.[21]

The development of antiproton Penning traps has progressed extremely well over the last 10 years. The PS200 experiment[22] trapped over 10^6 antiprotons for periods of hours. This is seen as a means of soon being able to confine up to 10^{12} antiprotons with transfer to a remote site for periods of several months.[23,24] Work is currently underway for development of a magnetic degrading spectrometer that will simply and inexpensively decelerate antiprotons into such portable traps. This approach is adequate for some important commercial applications and demonstrating fundamental propulsion concepts,

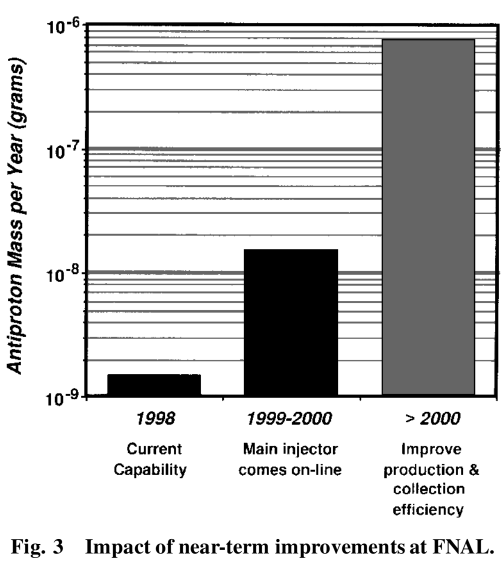

Fig. 3 Impact of near-term improvements at FNAL.

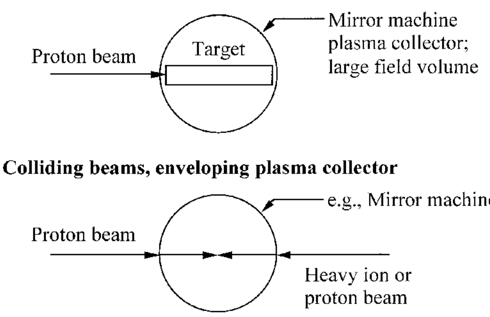

Fig. 4 Concepts for milligrams per year production facility.[13,14]

such as generation of subcritical microfission reactions and plasma formation as a precursor to fusion reactions. However, it will not be capable of providing the much larger quantities needed for direct propulsion applications. In this case, a more efficient decelerator section will be required to achieve production rates equivalent to ~ 1 μg per year. An antiproton decelerator that accomplishes this does exist at CERN, and in the case of FNAL would cost about $\$10^7$ to construct.

If the anticipated demand from the scientific community, NASA, and the commercial sector continues to grow, then investment in a completely new production-oriented facility would probably be warranted.[25] In the 1980s, the Rand Corporation studied development of such a capability and concluded that a capacity of several milligrams per year to possibly 1 g per year could be achieved with a new machine costing $\$3$–$10 \times 10^9$ (Refs. 13 and 14). Fixed target and colliding beam facilities were considered (Fig. 4), both capable of producing annual antiproton yields in the milligram to gram range. A comprehensive research and development program required to implement such systems was considered. Among the topics addressed were accelerator types (including intense, rapid cycling synchrotrons and high repetition-rate linacs), targeting, cooling of particle beams, plasma collection lenses, and large aperture collector rings.

Note that a multibillion dollar investment in such a capability is consistent with that of some previous major national science projects, and the design of such a facility falls well within the realm of known technology. In fact, the basic production process would be very similar to the current method of creating antiprotons from collisions of protons with high-Z targets. However, improvements, such as higher-Z accelerated particles and more efficient collection/focusing devices, would enhance efficiency considerably.

For capacities above 1 g, which would support a highly evolved transportation infrastructure within the solar system and trips into interstellar space, a completely new production technology is necessary. Several methods look promising, but all are at the very early stages of technological maturity.

Other issues are how to store groups of antiprotons of this scale and containment of the stored energy on this scale. Again, the energy stored within 1 g of antimatter is roughly equivalent to that delivered by 23 Shuttle ETs. A systematic approach to safe storage of such quantities is required, as has been done with other highly energetic and reactive materials. Studies of high-density storage of antimatter are underway and are an important step along this critical pathway.

Antimatter Production Costs

The costs of producing batches of antimatter on demand are not well characterized because the facilities do not yet provide this function as an actual service. FNAL is beginning to recognize the existence of an incipient demand outside the high-energy physics community. Although less experienced than FNAL, Brookhaven National Laboratory has recently expressed interest in producing antimatter for external customers; however, Brookhaven's facilities are much less developed than those at FNAL.

From our earlier analysis, the current cost of producing 1 μg of antimatter is $\$6.4 \times 10^9$. If we assume present production levels, the antimatter needed to support highly ambitious ACMF or AIM missions ($\sim 100\ \mu$g) would cost 6.4×10^{11}, much too high for practical considerations. In addition, the extremely low production rate would require an unreasonably long fill time on the order of hundreds of years. The situation looks discouraging until we account for the anticipated improvements to the current production capacity. In this case the costs would go down by at least two orders of magnitude to $6.4 \times 10^7 / \mu$g or 6.4×10^9 for a 100-μg mission. This is too expensive to support even occasional missions and is certainly prohibitive for anything above the 10-μg level. However, this cost certainly permits ground-based testing and demonstration of antimatter-assisted fusion/fission propulsion technology, which would require quantities of only 1 μg or less.

For actual missions, especially regular excursions to the outer solar system, there will be a need for investment in a new, dedicated facility. For antimatter requirements in the ~ 1 mg range and above, costs would have to be based on the capabilities of a new facility. In the preceding section, the initial cost for such a capability was estimated to be $3–10 $\times 10^9$ (Refs. 13 and 14). Production efficiencies would be much greater. If we assume an η_{tot} of 3.9×10^{-5} and the power grid costs from before, the costs could come down by nearly three more orders of magnitude to $\sim$ $6.4 $\times 10^4 / \mu$g. In this case the antimatter cost for a 100-μg mission would be $6.4 $\times 10^6$. At such values, antimatter becomes affordable enough to support a space transportation infrastructure based on some form of antimatter-assisted fission/fusion.

Conclusions

We have completed a study that: 1) evaluated the antimatter requirements for various propulsion concepts over a range of missions and velocity requirements, 2) compared these requirements against the capabilities of the existing antimatter production infrastructure, 3) compared these again assuming the improved capability expected over the next several years, and 4) estimated antimatter costs in dollars per microgram for both the current and improved infrastructure.

Results show that the antimatter costs associated with conventional antimatter rockets, that is, systems that rely on antimatter as the sole source of propulsive energy, are too high to be seriously considered for anything other than missions to nearby stars. Even missions within the solar system and into near-interstellar space would require production rates six to nine orders of magnitude greater than the existing infrastructure.

Antimatter-assisted fission/fusion, however, holds considerable promise for near-term applications. Although this form of propulsion could not be used for trips to the stars, it does provide excellent performance for missions within the solar system and near-interstellar space. The requirements for antimatter are on the scale of 1–100 μg per mission, which with the current infrastructure equates to an antiproton cost from $6.4 $\times 10^9$ to $6.4 $\times 10^{11}$. However, with several upgrades that could be incorporated in the near term, the cost could drop by at least two orders of magnitude to $6.4 $\times 10^7/\mu$g. This would enable development and demonstration of these technologies, which could justify investment in a dedicated facility based on existing production technology. Such a facility could support mission requirements at a cost from $6.4 $\times 10^4$ to $6.4 $\times 10^6$ per mission. These costs are certainly within the range of economic feasibility and suggest that antimatter-assisted fission/fusion may be a viable first step in applying antimatter for space propulsion.

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