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Mass Production of Antimatter for High-Energy Propulsion

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Theoretical and experimental work completed during the past decade indicates that interstellar propulsion systems based on the annihilation of antiprotons in a propellant will be feasible during the next several decades. The major technical difficulty appears to be the efficient production of antimatter. Estimates based on the use of currently available technologies indicate that the equipment required to produce and store antimatter would be inefficient and expensive. Hence, potentially more efficient processes should be examined. Currently, antiprotons are produced by colliding high-energy protons with stationary heavy-element targets, such as tungsten. Other approaches, for which experimental data are available, indicate that there are production methods that are more efficient. Several of these have been examined, and some show a significant improvement in efficiency, but they may be difficult to implement. Two methods examined will be discussed along with some technical advantages and disadvantages. In the first method, antiprotons and pions are collected from the collision of high-energy protons and a heavy-element target. Many more pions are produced than antiprotons. The pions are then directed toward the same target or a different target. The collision of pions and heavy nuclei have a higher probability for the production of antiprotons and would significantly increase the number of antiprotons produced. In the second method, a recirculating electron/positron collider would produce multiple collisions near a resonance for producing antiprotons by using beam wigglers as in free-electron lasers. This technique would allow a significant increase in the number of interactions that would occur and would proportionally increase the antiproton production.

Nomenclature

c = speed of light
$\dot{E}_0$ = energy storage rate
e^- = electron
e^+ = positron
I = beam current
J/ψ = charm–anticharm resonance particle
K^+, K^- = kaons
L_0 = luminosity
l = beam interaction length
$\dot{M}$ = mass injection rate
m_p = proton rest mass
n = neutron
P_0 = power
p = proton
$\bar{p}$ = antiproton
q_e = electron charge
S_0, s = center of mass energy
α = constant parameter
γ = photon
ε, η = efficiencies
θ = scattering angle
μ^+, μ^- = muons
$\nu_e, \bar{\nu}_e$ = electron neutrinos
$\nu_\mu, \bar{\nu}_\mu$ = muon neutrinos
π^+, π, π^0 = pions
ρ_0 = rho resonance particle
σ, σ_ψ = cross sections

Introduction

RECENT investigations have shown that it may be possible to store energy in the form of antimatter, providing an extremely high-energy-density storage mechanism.[1] The energy would be released by annihilating the antimatter with equal quantities of matter. The energy from the annihilation can either be used directly, or can be used to heat a working fluid.[1,2] The particles would most likely be stored in the form of antihydrogen.

Antimatter propulsion makes use of the annihilation of antiprotons with ordinary matter. For example, when an antiproton $\bar{p}$ and proton p annihilate,[2] the products of the annihilation are generally pions π, or

$$\bar{p} + p \rightarrow m\pi^0 + n\pi^+ + n\pi^- \tag{1}$$

Pions, to a first approximation, can be taken to be the particles that transmit the strong force. The strong force is responsible for binding the protons and neutrons together in an atomic nucleus. The number of neutral π^0 and charged pions $\pi^\pm$ created are approximately equal with

$$m \approx 2, \qquad n \approx 1.5 \tag{2}$$

The pions are unstable with the neutral pions decaying almost immediately (a mean life of 0.84×10^{-16} s) into high-energy gamma rays γ:

$$\pi^0 \rightarrow \gamma + \gamma \tag{3}$$

The charged pions decay into muons μ and an associated neutrino ν_μ

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \tag{4}$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \tag{5}$$

Muons are heavy electrons (about 200 times the electron mass), and neutrinos are generally believed to be massless. Neutrinos are quite penetrating and readily pass through matter without interacting. The muons are unstable and decay into electrons e and the appropriate neutrinos, according to

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \tag{6}$$

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \tag{7}$$

The final products of the reaction will be gamma rays, neutrinos, electrons, and positrons; i.e., antielectrons. If the electrons and positrons combine, they will annihilate according to

$$e^+ + e^- \rightarrow \gamma + \gamma \tag{8}$$

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Table 1 Summary of elementary particle properties

Particle	Antiparticle	Charge	Mass, MeV	Mean life, s	Principal decay made
p	$\bar{p}$	+1	938.3	Stable	——
e^-	e^+	−1	0.511	Stable	——
μ^-	μ^+	−1	105.7	2.2×10^{-6}	$e^- + \nu_e + \bar{\nu}_e$
ν_e	$\bar{\nu}_e$	0	0	Stable	——
ν_μ	$\bar{\nu}_\mu$	0	0	Stable	——
γ	γ	0	0	Stable	——
π^+	π^-	+1	139.6	2.6×10^{-8}	$\mu^+ + \nu_\mu$
π^0	π^0	0	135.0	8.4×10^{-16}	$\gamma + \gamma$
π^-	π^+	−1	139.6	2.6×10^{-8}	$\mu^- + \bar{\nu}_\mu$

Hence, if complete annihilation occurs, the final products will be gamma rays and neutrinos. A summary of characteristics of the reaction products is presented in Table 1.

The charged products produced readily interact with matter, depositing some fraction of their kinetic energy during collisions with the electrons and nuclei. The charged particles can also be directed or trapped by magnetic or electric fields. Neutral reaction products can be considered a loss, although the energy from the gamma rays could be absorbed by using large quantities of matter.[2]

Calculations and simulations indicate that specific impulses for space-based propulsion systems will vary from ~2000 s at high thrust, to over 10,000,000 s at low thrust.[2]

A primary difficulty in developing antimatter-driven devices is the efficient production of antiprotons. If energy stored in the form of antimatter could be produced at an overall efficiency on the order of 2.5×10^{-4}, an increase of at least 10^4 over current capability, then it would be competitive with having to lift conventional propellents into Earth orbit.[1,3] Currently, antimatter is produced with an efficiency of $\sim 2.5 \times 10^{-8}$ by impacting a heavy element target with high-energy protons.[3]

The remainder of this paper will primarily cover concepts that may be useful for the efficient production of antimatter.

Creation of Antiprotons

Antiprotons can be created by colliding a variety of high-energy beams with either stationary targets or other beams.[4] For example, the beams or the targets can consist of protons, electrons, pions, photons, kaons K, or heavy nuclei. Some of the reactions that produce antiprotons $\bar{p}$ are[5,6]

$$\pi^{\pm} p \longrightarrow \bar{p} X \tag{9}$$

$$\pi^{+} \pi^{-} \longrightarrow p \bar{p} \tag{10}$$

$$e^{+} e^{-} \longrightarrow p \bar{p} \tag{11}$$

$$\gamma p \longrightarrow \bar{p} X \tag{12}$$

$$K^{\pm} p \longrightarrow \bar{p} X \tag{13}$$

where X represents all other particles produced in the reaction. It appears it may be more efficient to use beams of heavy nuclei Z than protons. Hence, colliding heavy ion beams such as

$$ZZ \longrightarrow \bar{p} X \tag{14}$$

may prove to be more effective than

$$pp \longrightarrow \bar{p} X \tag{15}$$

or even

$$pZ \longrightarrow \bar{p} X \tag{16}$$

which is the reaction currently used to produce antiprotons. Figure 1 presents a summary of many reactions that could be used for the creation of antiprotons.

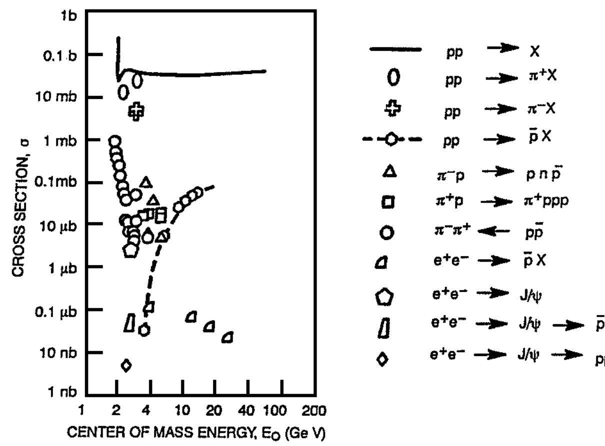


Fig. 1 Antiproton production-related cross sections.

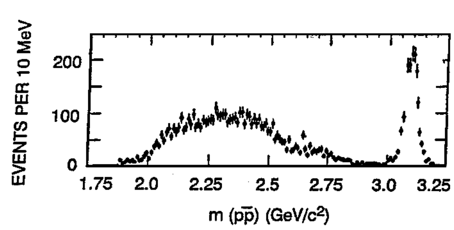


Fig. 2 Proton-antiproton mass for a two-prong J/ψ decays produced in e^+e^- annihilations.[21]

It may also be possible to produce antiprotons copiously by taking advantage of the properties of a high-energy resonance.† Collisions of positrons and electrons at exactly 3.097 GeV c.m. energy have a large probability of producing the narrow J/ψ particle. The J/ψ decays significantly (0.022% of the decays) into antiprotons or antineutrons, (see Fig. 2):

$$e^{+} e^{-} \longrightarrow J/\omega \longrightarrow N \bar{N} X \tag{17}$$

This could provide an efficient source for producing antimatter.[5]

The reactions using either positrons or pions appear to be attractive from the standpoint of production efficiency, but it is difficult to produce tight beams of pions before they decay, and the cross section for reaction (17) is so small that extremely high beam currents will be required. Even the use of heavy ions appears to have lower cross sections than initially anticipated because most of the collisions are glancing, resulting in considerably fewer antiprotons.

The production of pions is important if reactions such as (9) or (10) are used. Pions are produced in significant quantities, when compared to antiprotons, in proton–proton or heavy nuclei collisions.[7] The pions can be collided with other target nuclei, or focused and collided head on, to add to the antiproton yield from the initial reactions (14–16). Reaction (17) also produces significant quantities

†Mannheim, P., private communication, Univ. of Connecticut, Storrs, CT, 1989.

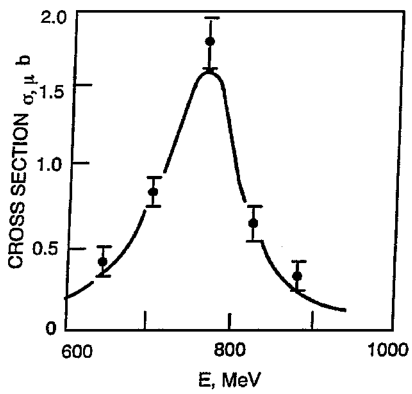


Fig. 3 Resonance for $e^+e^- \rightarrow \pi^+\pi^-$[8].

of pions.[8] Pions can also be produced by the decay of lower energy resonances. The ρ^0 particle decays more than 99.9% of the time into a pair of oppositely charged pions.[8] The entire reaction is

$$e^+e^- \rightarrow \rho^0 \rightarrow \pi^+\pi^- \tag{18}$$

The ρ^0 resonance is illustrated in Fig. 3 (Ref. 9). At the J/ψ resonance the cross section for

$$e^+e^- \rightarrow J/\psi \rightarrow \pi^+\pi^- \tag{19}$$

is about 3 nb from Fig. 1 and Ref. 8, which is about 1/1000 of the ρ^0 resonance cross section (from Fig. 3). Hence, it may be possible to make use of energy lost in creating nonantiproton particles to increase the efficiency of antiproton production.

The reason pions have a greater probability of producing antiprotons, at high energy, can be illustrated by considering the following reactions:

$$pp \rightarrow ppp\bar{p} \tag{20}$$

$$\pi^- p \rightarrow np\bar{p} \tag{21}$$

$$\pi^-\pi^+ \rightarrow p\bar{p} \tag{22}$$

The pion in reaction (21) can be produced by

$$pp \rightarrow \pi^- X \tag{23}$$

If the beam of protons impacts stationary proton targets, e.g., liquid hydrogen, then reaction (20) requires a minimum beam energy of 5.3 GeV; whereas reaction (21), together with reaction (23), requires a minimum beam energy of 4.1 GeV (Ref. 10).

The process represented by Eq. (21) at high energies, i.e., at energies where the rest mass energy is small compared with the kinetic energy, should have a larger cross section than the process represented by Eq. (20) (see data in Ref. 11). This can be illustrated by noting that a pion consists of a quark–anti-quark pair and a proton consists of three quarks (an antiproton is three antiquarks). Then the number of quarks involved in reaction (21) is less than in reaction (20). Equation (22) involves even fewer quarks.

An estimate of the high-energy cross section σ can be obtained from quantum chromodynamics,[12] as

$$\lim_{s\rightarrow\infty} \frac{d\sigma}{dt}(A + B \rightarrow C + D) = f(\theta)s^{2-(n_A+n_B+n_C C+n_D)}$$

$$= f(\theta)s^{2-n_H} \tag{24}$$

where

$$s = (p_A + p_B)^2, \qquad t = (p_A - p_B)^2, \qquad -t/s = (1 - \cos\theta)/2$$

θ is the scattering angle; p_A, p_B is the momentum of particle A, B; and n_A, n_B, n_C, and n_D are the minimum number of fields in each hadron; i.e., the number of quarks. Applying Eq. (24) to each of the reactions (20–22) produces the results in Table 2. Hence, at a high enough energy, regardless of the function $f(\theta)$, the last reaction has the highest probability and results in the most efficient transformation of kinetic energy into rest mass energy.

Table 2 High-energy antiproton cross section

Reaction	$n_H = n_A + n_B + n_C + n_D$	$\lim_{s\rightarrow\infty}(d\sigma/dt)$
$p + p \rightarrow p + p + p + \bar{p}$	18	$f_1(\theta)s^{-16}$
$\pi^- + p \rightarrow p + n + \bar{p}$	14	$f_2(\theta)s^{-12}$
$\pi^- + \pi^+ \rightarrow p + \bar{p}$	10	$f_3(\theta)s^{-8}$

Experimental data for some of the cross sections of reactions (9–23) can be found in many compilations, e.g., Refs. 4, 5, 13, and 14. These can be extended to areas where data do not exist by using theoretical models. For example, one particle exchange at low energies,[14] Regge pole exchange at higher energies[15]; and quantum chromodynamics[16] or quark-counting rules[12,17] at the highest energies can be used to extend the experimental data.

It must be noted that although heavy ion collisions have a high effective beam luminosity, the cross section does not go up as a product of nucleon numbers because glancing collisions make most of the nucleons spectators.[7]

As an example of cross-sectional calculations that can be made, consider the creation of J/ψ particle using colliding electron–positron beams, and the subsequent decay into proton–antiproton pairs. At a c.m. energy of 3.097 GeV, the cross-section is ~2500–3000 nb (Ref. 13). This is to be compared with the cross-section at the same energy for

$$e^+e^- \rightarrow e^+e^- \qquad \text{with} \qquad |\cos\theta| \leq 0.6 \tag{25}$$

where θ is the polar angle from the beam direction.

Reaction (25) has a cross section of ~150 nb (Ref. 13). Hence, at 3.097 GeV, the dominant reaction should be

$$e^+e^- \rightarrow J/\psi \tag{26}$$

For subsequent calculations, it will be assumed that the cross section for reaction (26) is 3000 nb and that five-sixths of the scattering will produce J/ψ particles.

The second part of the reaction is the decay of the J/ψ particle into nucleon–antinucleon pairs, i.e.,

$$J/\psi \rightarrow N\bar{N}X \tag{27}$$

From Refs. 18 and 19, the decay [reaction (27)] has a probability of ~3%, whereas the probability to decay into a proton–antiproton pair only,

$$J/\psi \rightarrow p\bar{p} \tag{28}$$

is ~0.2% (Refs. 20 and 21). Reaction (28) is particularly important because the antiprotons must come off with exactly one-half the c.m. energy. i.e., 1.548 GeV, and, hence, their total momentum is precisely known. However, the angular distribution is nearly isotopic; specifically, Ref. 21 gives

$$\frac{dN}{d(\cos\theta)} = N_0(1 + \alpha\cos^2\theta) \tag{29}$$

where

$$\alpha \approx 0.61 \pm 0.23 \tag{30}$$

This is a relatively flat distribution and beam optics must be designed to accept wide distributions in direction, but with a specific total momentum. Theory indicates that[13]

$$\alpha \approx 0.40 \tag{31}$$

which is at the low end of the experimental measurement.

Summarizing, the best potential reactions are 1) those with a high cross section (in recirculating devices the cross section should also be high compared with the total cross section, and 2) those that produce easily collectable antiprotons.

In the preceding discussion, the antiprotons are created from the excess beam kinetic energy. This excess energy does not necessarily need to come from a particle beam, but can also be obtained from the random particle motion in a high-temperature plasma.[18,22] The plasma temperature ($\sim 10^{12}$ K) must be orders of magnitude higher than that required for fusion, and only high-energy particle beams will be considered for the remainder of this paper.

Particle Collection

The collection of the antiprotons or pions created in a high-energy reaction is a major difficulty in devising systems for the efficient production of antimatter. Collection efficiencies are enhanced, e.g., if 1) only negative (or only positive) particles need to be collected; or 2) the angular distribution of the particles has a preferred direction; or 3) the momentum of the particles has a preferred magnitude, as in reactions (26) and (28); or 4) any combination of 1–3.

The efficient generation of antimatter would require advances in all aspects of beam acceleration, focusing, and separation for this energy storage mechanism to be competitive with other storage mechanisms. Nevertheless, efficiencies for generating and collecting antimatter can be approximated based on current designs.[1] As an example, consider the generation of antimatter from the collision of electron–positron beams at 3.097 GeV by reactions (26) and (28). Consider the accelerator to be a recirculating electron accelerator (a nonrecirculating accelerator will not be efficient with cross sections on the order of 1 μb). Counter-rotating electron and positron beams will be used and an efficiency η of 20% will be assumed. Not only can positrons be readily produced, but they could also be obtained from naturally occurring radioactive decay. The energy storage rate in a process that produces antimatter $\dot{E}_0$ is given by

$$\dot{E}_0 = 2\dot{M}(\bar{p})c^2 = 2\dot{N}(\bar{p})m_p c^2 \qquad (32)$$

where $\dot{M}(\bar{p})$ is the rate at which antimatter is generated, c is the speed of light, m_p is the mass of a proton, and $\dot{N}(\bar{p})$ is the rate at which antiprotons are created.

The rate at which antiprotons are produced is given by

$$\dot{N}(\bar{p}) = f(p\bar{p})\dot{N}_\psi = f(p\bar{p})\sigma_\psi L_0 Il/cq_e \qquad (33)$$

where $f(p\bar{p})$ is the fraction of J/ψ particles decaying to proton–antiproton pairs (about 0.002), $\dot{N}_\psi$ is the rate at which J/ψ particles are created, σ_ψ is the cross section for generating J/ψ from e^+e^- collisions (3000 nb), L_0 is a beam luminosity, I is a beam current, l is the length over which the beams collide, and q_e is the charge of an electron.

The input power is given by

$$P_0 = \frac{IS_0}{\eta q_e}[1 - \exp(-\sigma_T L_0 l/c)] \approx \frac{\sigma_T L_0 l S_0 I}{\eta q_e c} \qquad (34)$$

where S_0 is the c.m. energy (3.097 GeV), and σ_T is the total cross section for all e^+e^- reactions at 3.097 GeV (3600 nb).

Taking typical values $\dot{M}(\bar{p}) \sim 10$ mg/year, $L_0 \sim \frac{1}{6} \times 10^{32}$/cm^2-s, (Ref. 12 and 14), $l \sim 100$ cm, and $\sigma_T/\sigma_\psi = 1.2$. Then from Eqs. (17–19) we find

$$I \sim 10^6 A \qquad (35)$$

while the total efficiency ε is

$$\varepsilon = (\dot{E}_0/P_0) \sim 10^{-3} \qquad (36)$$

This crude estimate for the efficiency approaches Forward's[1] goal of 0.25×10^{-3}.

The current for e^+e^- collisions is clearly well beyond current technology, but can be reduced by employing reactions with higher cross sections. For example, the cross section for reaction (18) is about 10^3 times longer than for reaction (19) (see Figs. 1 and 3), making the current required for reaction (18) be 10^{-3} of that required for reaction (19). From Fig. 1, the current for reaction (10) is about 10^{-5} of the current for reaction (11). Hence, if pions could be removed from a reaction and tightly focused before a significant fraction decay, then it would be possible to manufacture antiprotons with significantly smaller facilities than e^+e^-, proton, or heavy ion beam facilities.

Lower beam energies have several benefits. Particles to be collected will require less cooling, magnetic fields for focusing beams will be smaller, the energy efficiency is higher, etc. A major disadvantage is the large angles through which the produced particles will emerge. Collecting and focusing particles over a full 4π spherical angle presents significant difficulties.

A concept for the construction of a 4π collector can be illustrated by considering Fig. 4. In Fig. 4, a particle is created at the origin and emitted at the angle θ_0. The particle travels in a straight line for a given distance, where it enters a circumferential magnetic field and is then turned through a circle of constant radius until it is moving at a specified angle with respect to the r axis, where it leaves the field. The particle then travels in a straight line until it intercepts the z axis. Note that the spread in momentum in the direction of

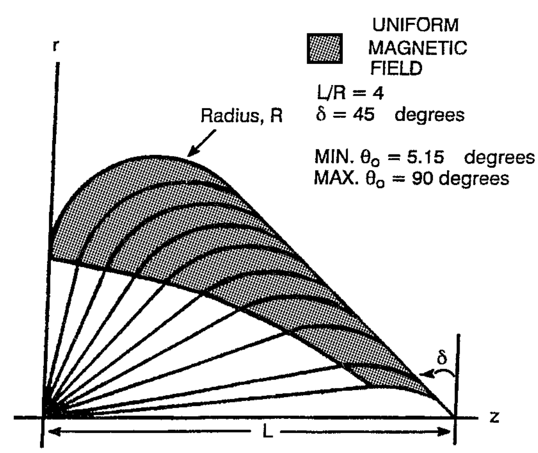
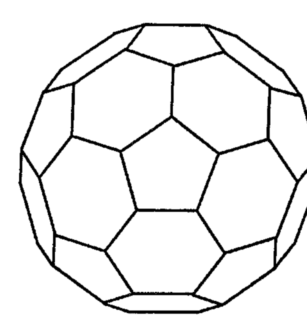


Fig. 4 Particle trajectories for various emission angles, θ_0.

Fig. 5 Soccer-ball 4π spherical collector.



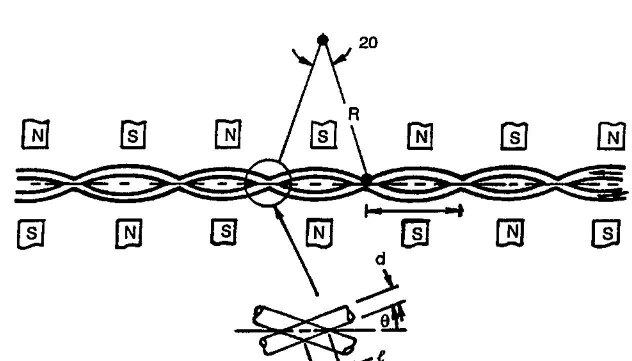


Fig. 6 Wiggler geometry for intersecting various interaction length. Magnetic field is perpendicular to plane of figure.

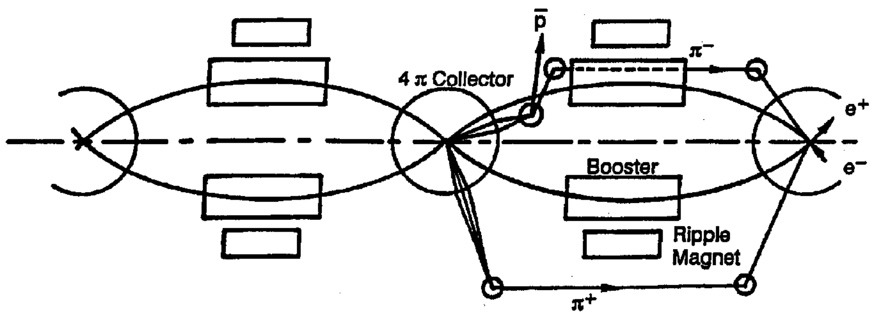


Fig. 7 Antiproton and pion focusing in electron–positron collider. Magnetic field is perpendicular to plane of figure.

travel can be removed by utilizing cooling techniques, in particle accelerators and through synchrotron radiation emission.

The entire 4π collector can be constructed by utilizing the soccer-ball geometry illustrated in Fig. 5 (from Ref. 6). The edges of the 32 polygon faces are equal in length. An axisymmetric magnetic field is present in each of the polygon's spherical segments, with the center of the field along the perpendicular through the center of each polygon face. Hence, the currents could be along the windings of torridal solenoids. The torridal solenoids would have their axis perpendicular to the polygon faces.

Two points on particle collection are worth noting. First, the focusing magnetic fields for 4π spherical collections may require the conductors be present in the regions where particles are moving. Hence, the conductors will have to be resistant to radiation damage. The new ceramic superconductors sometimes show some resistance to radiation damage; therefore, they may be ideally suited as the conductors. Second mass spectrometer designs may be useful as concepts for developing 4π spherical collectors. The collection efficiency should be sufficient based on current design practice.[23,24]

Previous analyses[5] have indicated that for electron–positron collisions at the J/ψ energy, the interaction lengths will have to be about 1 m for the production of 10 mg of antimatter per year. If recirculating electron–positron beams colliders are used, then a total beam current of at least 100,000 A will be required. An interaction length of 1 m is large by current standards, but may be attained by using wiggler magnets, as in a free electron laser (see Fig. 6). Assuming small angles, a beam diameter of 0.1 mm, a bending radius of 1.0 m, and then about 200 wiggler magnet sections are needed to produce a total interaction length of 1 m. The total length for all of the interactions is at least 4 m. It should be noted that there are many concepts that could significantly shrink the size of free-electron lasers.[19]

If the free-electron laser wiggler magnets are moved sufficiently far apart, particle collectors can then be placed at the intersection sites. Debris, e.g., pions, from the reactions can be collected in addition to the antiprotons collected. The debris, such as pions, can be refocused, and the antiprotons collected, as illustrated in Fig. 7. Energy boosts can be provided between the interaction sites for the electron and the positron beams, and if necessary for the debris. This system would be considerably larger. The collectors will be about 1 m in diameter for magnetic fields on the order of 1 T, making the total length on the order of 1 km for a facility producing 10 mg/year. If the electron–positron collisions occur at the J/ψ energy, then only decays resulting in two pions (and possibly one or more gamma rays) will have pion energies sufficient to produce a proton–antiproton pair. If lower energy pions are refocused, then their energy would have to be boosted.

Conclusions

Obviously, antiproton annihilation rockets will not be ready for use tomorrow, but their potential performance is enormous. In fact, it has been shown that antiproton annihilation propulsion will always cost less than other rocket-based propulsion systems, chemical or nuclear, for a sufficiently high-performance mission. The amount of antimatter required for a mission can be readily estimated. For example a 10-ton transfer from low Earth orbit to geosynchronous orbit and back requires about 4 mg of antimatter.[2] A 500-ton transfer to Mars and back in 150 days requires about 31 g of antimatter (using the analysis in Ref. 8); and a 500-ton, 45-year flyby of Alpha Centauri (about 4 light years distance) requires about 12 kg of antimatter. These estimates are extremely large by current standards.

Antiprotons are created in high-energy particle accelerators. Antiprotons can be produced using protons, heavy ions, mesons, or particle resonances. They can be cooled by using degraders and electrons. Positrons can be readily created and used to neutralize the antiprotons, in the form of antihydrogen, and it appears the antihydrogen can be cooled and stored indefinitely.

Summarizing, antiprotons can be manufactured, stored, and used for propulsion. The problem remains one of economics. The quantity of antiprotons manufactured and stored today is several orders of magnitude too small, and the expense associated with scaling up to significant quantities would be astronomical. Therefore, the problem associated with antiproton annihilation propulsion is the reduction of production costs to levels where currently planned missions can be performed in a cost-effective manner.

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