NIAC Phase I Progress Report
Antimatter Driven Sail for Deep Space Missions

Final Report for Phase I

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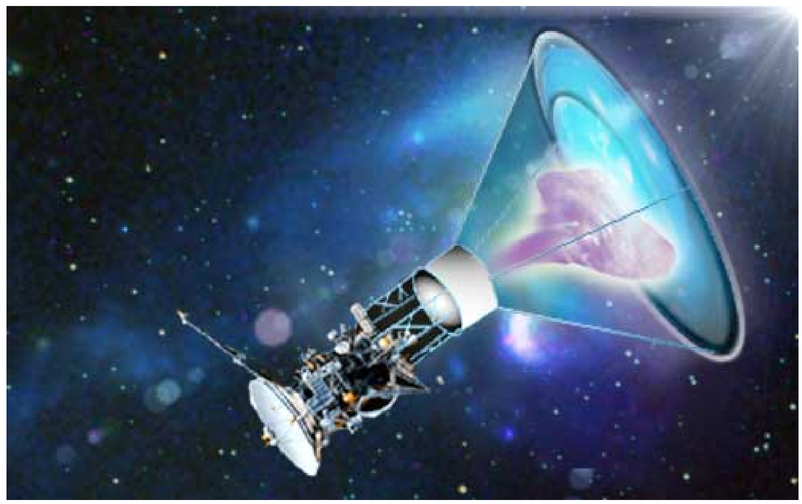
Executive Summary



The ultimate goal of this project is to identify and investigate an exploration architecture that would allow a light-weight instrument package to be sent to another stellar system. Due to the difficulty inherent in an interstellar mission, however, we have examined the architecture in Phase I under the auspices of a less demanding mission, i.e. sending a probe to 250 AU, the Kuiper Belt, in 10 years. Such a mission is still beyond the capability of NASA or any other agency using currently available technology.

We have examined three major areas during the Phase I study: Mission Architecture, Subsystem Technologies, and a Technology Roadmap. The Mission Architecture effort has focused on developing an integrated systems model to evaluate the performance of the entire spacecraft for a mission. The Subsystem Technologies investigation has examined 1) the fundamental reactions between the antiprotons and the sail material and the subsequent momentum transfer, 2) a concept for storing antihydrogen at high densities, and 3) an entirely new concept for electrical power production. The new electrical-power concept may have applicability to nearer-term space missions as a power supply if the availability of antiprotons becomes common. In developing the Technology Roadmap, we have examined the potential 1) for using recent developments in antiproton storage and anithydrogen formation to cerate a path to ultra-high density antihydrogen storage, and 2) for increasing production of antiprotons by modifying the existing Fermilab facility.

The Phase I project has been very successful. Our system analysis indicates that that a 10 kg instrument payload could be sent to 250 AU in 10 years using 30 milligrams of antihydrogen. This amount of antimatter is clearly within the production potential of the US within the next 40 years using currently accepted accelerator technologies. In addition, preliminary calculations also show that 17 grams of antihydrogen could send a similar probe to the next star, Alpha

Centauri, in 40 years. Previous investigations by JPL had concluded that kilograms of antimatter would be needed for an interstellar mission.

The system studies contained a variety of assumptions with regard to technology subsytems. First of all, the actual momentum transferred to the sail from antimatter-induced fission is in question and is a critical factor. The second issue is the feasibility of storing antihydrogen micro-pellets in solid-state integrated circuits. Finally, the development of a high specific-mass electrical-power supply based on Antimatter Fission Conversion is proposed based on currently available technologies. The combination of all these factors dictates the performance of the spacecraft.

The final result of this Phase I study is that the concept of sending an instrument package into really deep space to understand the major questions in astrophysics and cosmology may indeed be within our grasp. Major aspects of the architecture remain to be investigated but the first-cut assessment of the mission profile, the subsystem technologies, and the technology development path have all been identified. The antimatter driven sail may in-fact allow humanity to consider sending probes to the stars.

Mission Architecture

In order to evaluate the performance of the Antimatter Sail concept, we have developed an integrated systems model. The model incorporates the interplay between the various subsystems and the mission profile. Masses for the subsystems are calculated based on the relations we have developed and are often dependent on mission time, burn time (time under acceleration), sail size, antimatter storage assumptions, and, most importantly, the assumed number of uranium atoms being ejected per fission. This last parameter has a remarkably strong impact on the number of antiprotons required for a mission.

For the Phase I study, the design mission was to deliver a 10 kg instrument payload to 250 AU within 10 years. The 10 kg payload was assumed based on work done at JPL [1,2]. The mission was assumed to be a fly-by mission although the ability to tack or to stop at the final destination is within the capabilities of this concept. Consequently, the average velocity of the spacecraft was taken to be 116.8 km/s.

Sail

The primary question relative to the performance of this concept is the momentum delivered to the sail by the fission of the uranium. If just the two fission products are released then the momentum is determined by the velocity and mass of one of the products. The antimatter induced fission of uranium produces a spectrum of masses. The width of this distribution, however, is relatively narrow and can be approximated by using palladium-111 as the average fission product. The energy released in the fission is taken to be 190 MeV. Thus, the velocity of the fission product is $1.39\text{X}10^{7}$ m/s and the mass is $1.85\text{X}10^{-25}$ kg/atom. This velocity would equate to a specific impulse of 1.4 million seconds.

However, if neutral atoms of uranium are blown off in each fission event [3,4], then the energy of the event may be distributed among the blow-off mass. The result is that the momentum transferred to the sail is higher and the specific impulse is lower. Potentially, the number of atoms ejected per fission may be determined by the depth of penetration of the antimatter atoms which is determined by controlling the energy of the incident beam. Thus, the specific impulse of the system may be controlled or adjusted to match the requirements of each mission.

Consequently, we performed a parametric study using the number of atoms ejected per fission, Nat, as a free parameter. Figures 1-3 shows the results of this study. Figure 1 shows the specific impulse as a function of Nat. We have assumed that the energy released in fission is equally distributed among the atoms ejected. Figure 2 shows the dependence of the mass of antimatter required to perform the mission. The figure clearly depicts a minimum for Nat equal to around 15,000. This corresponds to a specific impulse of almost 7500 s. Figure 3 shows the masses of the uranium fuel and the spacecraft as a function of Nat. For Nat equal to 1, the specific impulse is over a million seconds and the fuel mass is small compared to the ship mass. As the specific impulse gets below 10,000 s, the mass of the fuel begins to dominate the ship mass.

For the mission under consideration, the optimum value for Nat, i.e. the value where the number of required antihydrogen atoms was a minimum, occurred at Nat=15,000. This value is within the range measured in previous experiments. Thus, for the system studies, we used the value of 15,000 atoms per fission.

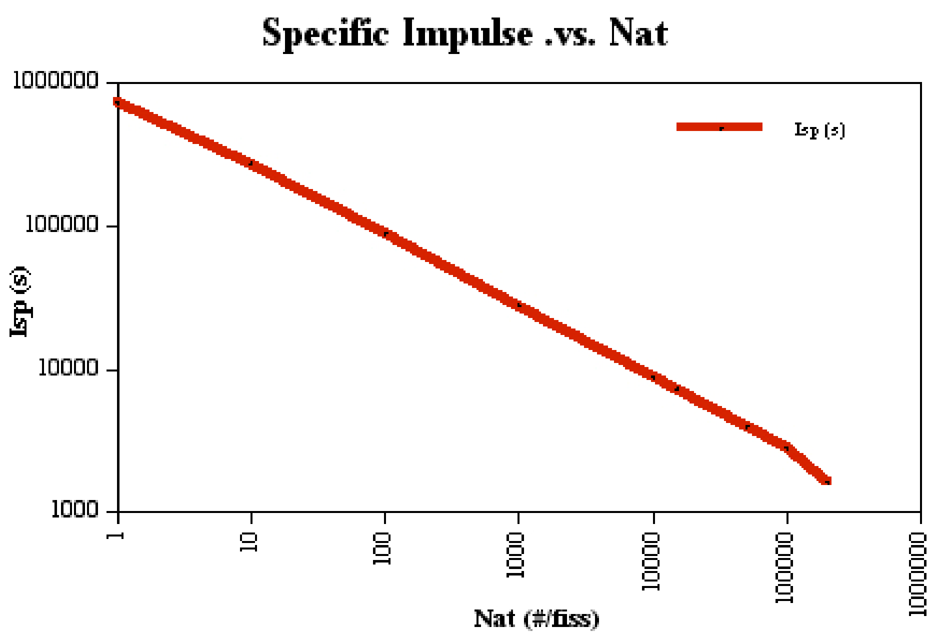


Figure 1. Plot of the specific impulse versus Nat, the number of atoms ejected per fission event.

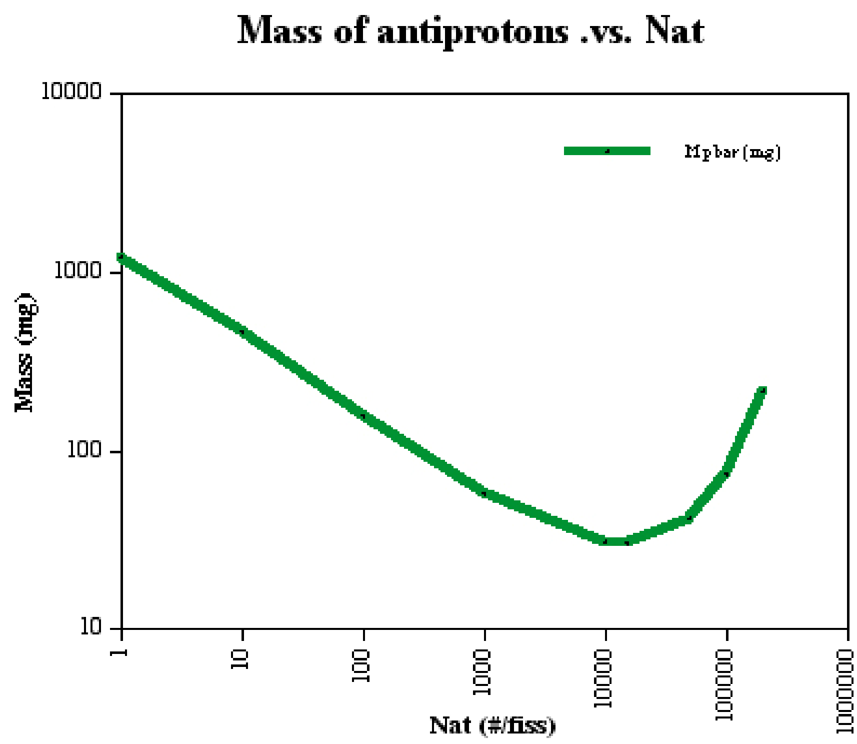


Figure 2. Mass antimatter as a function of Nat

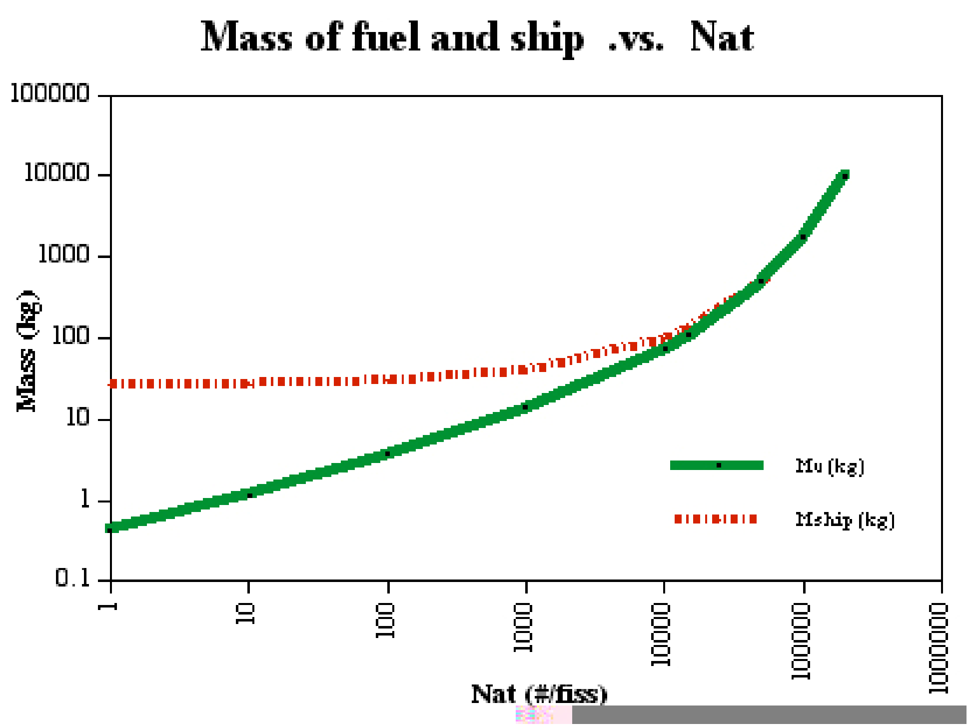


Figure 3. masses vs Nat

The culmination of the results of the integrated system studies is shown in Figure 4. The spacecraft has a sail that is composed of two layers- a carbon backing (sail) and a uranium coating (fuel). The entire sail is 5 m in diameter. The carbon layer is 15 microns thick (34 g/m2) and the uranium is 293 microns thick. The total mass of uranium is 109 kg.

The large area of the sail removes the requirement for active cooling. The sail is assumed to dissipate waste heat passively via black-body emission. We assumed an emissivity of 0.3 for both the carbon and the uranium. The steady state temperature of the sail would be 570 C, well below the melting point of uranium.

<u>Antihydrogen storage unit</u>

The antihydrogen storage system is held 12 m away from the sail via four tethers. A schematic of the storage system in shown in Figure 5. The storage system is an array of small chips resembling integrated circuit chips. Each chip, however, is not an electronic unit but contains a series of tunnels etched in a silicon substrate. Each tunnel is a sequence of electrodes. Each electrode pair forms a cell that contains a single pellet of solid antihydrogen. Each pellet holds around 10^{15} antihydrogen atoms and a charge of roughly 10^{-11} coulombs.

Each tunnel holds 67 cells. There are 100 tunnels per 4 cm long chip. Thus, each chip holds $1.6X10^{19}$ antihydrogen atoms. There are roughly 2000 chips in the storage assembly. Total number of antihydrogen atoms is $1.8X10^{22}$ or 30.45 milligrams. The entire mass of the storage unit is about 9 kg.

<u>Power</u>

Behind the storage unit, connected by a short truss of carbon-carbon ribs, is the electrical power supply. The power supply utilizes the concept of Antimatter Fission Conversion (AFC) developed in this project. The AFC concept is depicted in Figure 6. A designated number of storage units identical to those used to propel the vehicle are arrayed to point into the AFC cone. Antimatter injected into the conical region converts the fission product energy to light and then into electricity. Surrounding the conversion cell is a plenum of liquid lithium which transfers waste heat to a radiator. The radiator is composed of beryllium.

We assumed a power requirement of 400 w based on the specifications for the Voyager spacecraft [5]. The overall efficiency of the AFC unit is estimated to be 4.4%. Thus, around $2X10^{14}$ antiprotons per second are needed for the 400 w of electrical power. The power is generated on demand when communications back to Earth are indicated. The waste-heat radiator is composed of two sheets, diametrically opposed, with the edges facing the sail. The sheets, designed as fins with a roughly triangular cross section, have a total surface area of 3.5 m^2. The radiator temperature is 620 C. Total mass of the power unit is around 6.4 kg. Thus, the specific mass of the unit is 16 kg/kw.

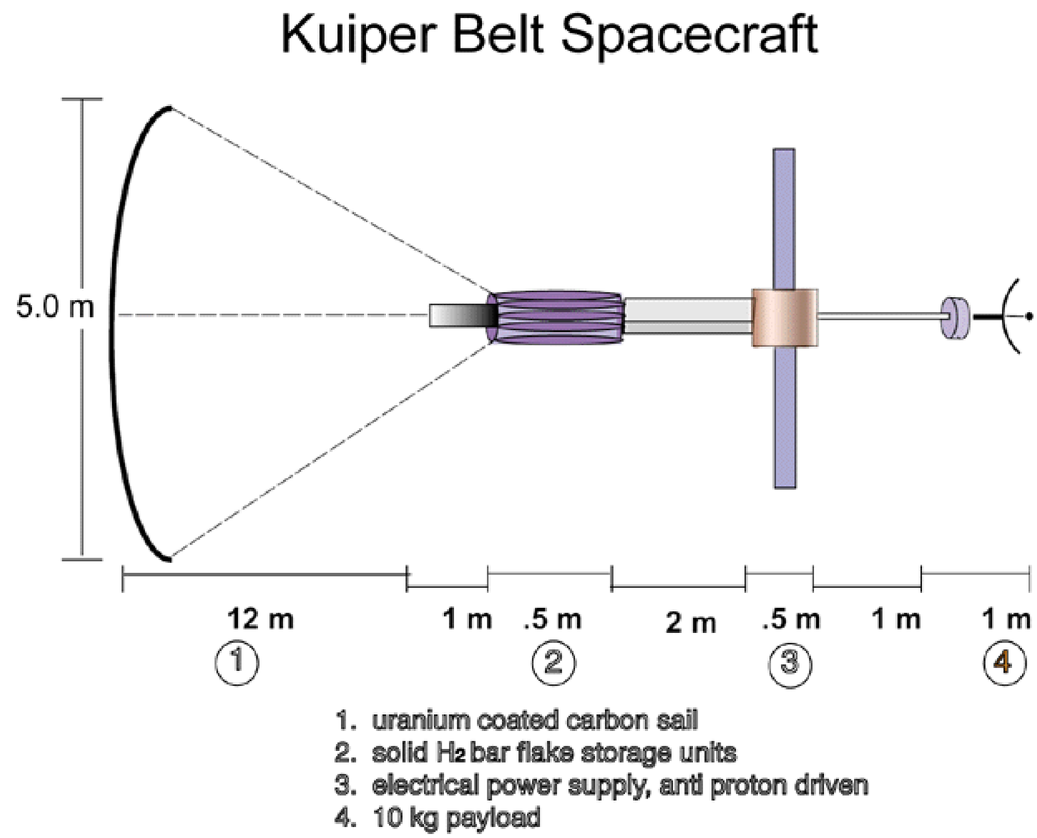


Figure 4. Antimatter Sail spacecraft based on integrated system studies.

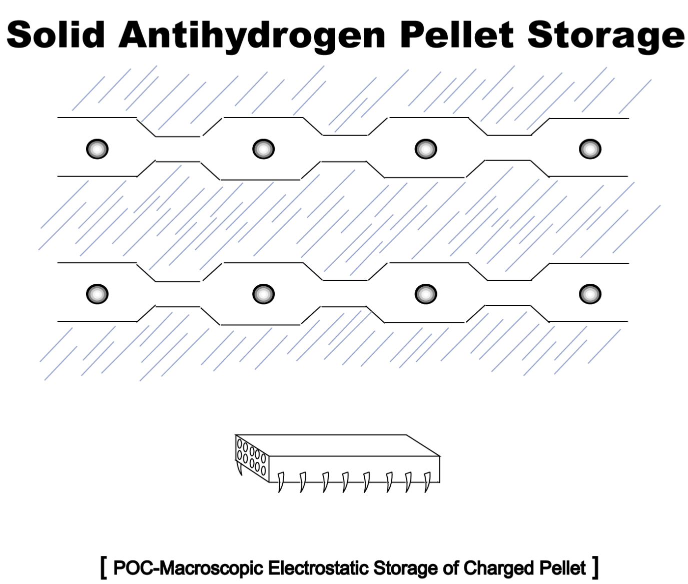


Figure 5. Schematic of the antihydrogen storage chip.

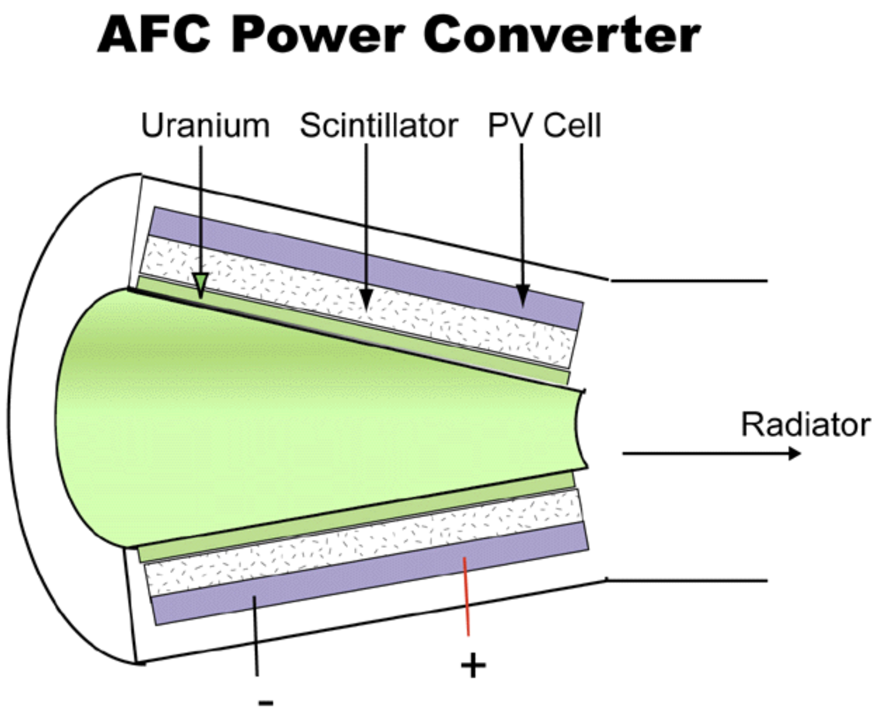


Figure 6. Schematic of the AFC power unit.

System

In an effort to assess the sensitivity of our system studies, we calculated the impact of increasing the dry-mass (e.g. in the power supply or structural material or instrument payload). The results of these calculations is shown in Figure 7. The values for the masses of antimatter, uranium fuel, and the entire spacecraft are shown as a function of the change in the dry mass. The results show that even if the dry-mass is doubled, i.e. increased by 26 kg, the mass of the ship only goes to about 280 kg and the amount of antimatter increases to 60 mg.

One unexpected result is that in order to achieve the minimum acceleration level of 0.006 m/s^2, the burn time had to shortened to 4 months. Thus, most of the mission time would be spent coasting -- not under acceleration. This increased the temperature of the sail and the antimatter expulsion rate but it also reduced the storage requirements of the antimatter.

The results of the calculations reveal that a Kuiper Belt mission could be achieved with this concept . The required amount of antimatter will be a few tens of milligrams. The total initial mass of the spacecraft will be on the order of 135 kg.

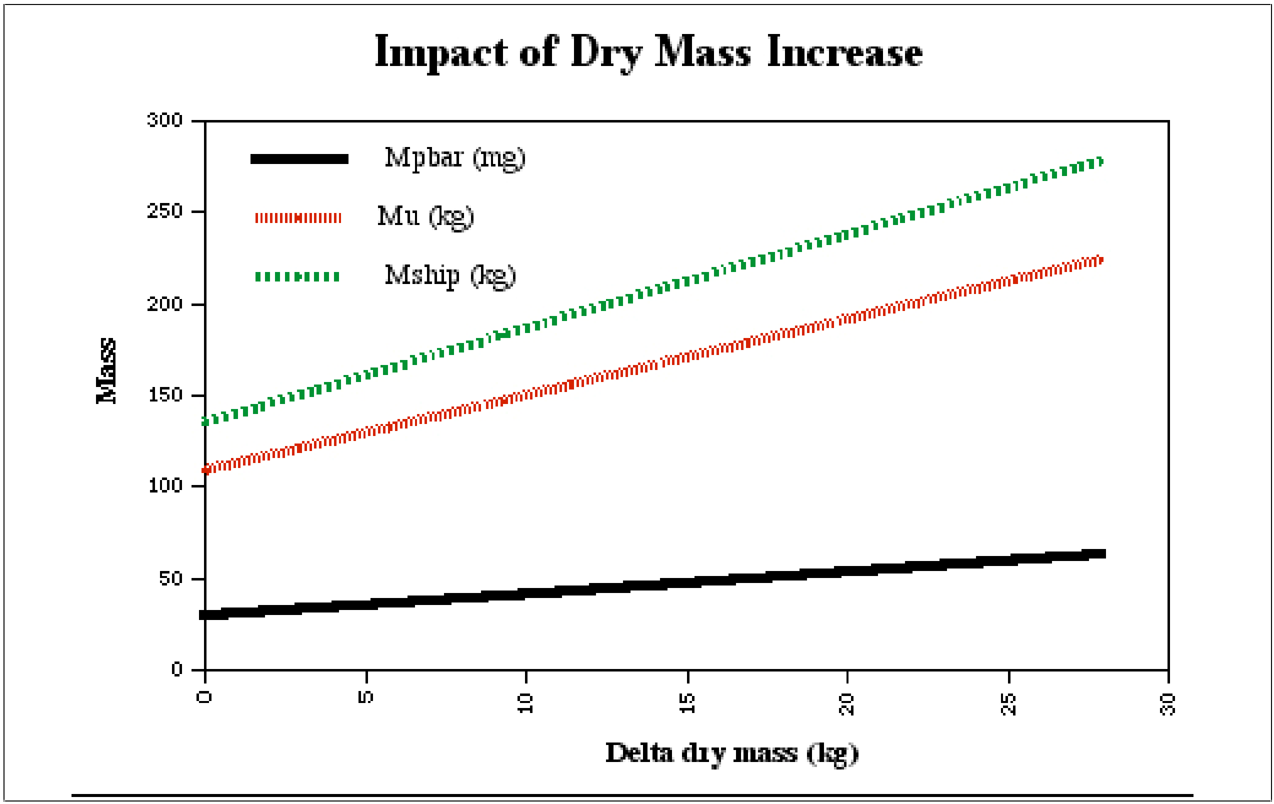


Figure 7. Sensitivity to subsystem masses

Subsystem Technologies

The specific technologies for the various subsystems have been described in the first two interim reports for this project. The revolutionary aspects of the technologies are:

1) use of the emission of fission products as a high specific-impulse propellant;
2) ability to produce, manipulate, and store antihydrogen in solid form as micro-pellets;
3) use of the antimatter induced fission process to induce fluorescence in a material that is "tuned" to a photovoltaic converter.

All of these technologies are based on sound physics principals but require verification and proof of concept experiments.

Technology Roadmap

Large Scale Antimatter Production

In order to fully realize the potential of antimatter as a means of accelerating spacecraft out into deep-space, it is necessary to increase the global production rate of antiprotons by a significant amount. At present the global production rate is approximately $5x10^{14}$ antiprotons/year, or 84 ng/year. According to Table 1, the Kuiper Belt mission requires $8x10^{22}$ antiprotons. Assuming that 80% of the global antiproton production can be delivered to one space exploration mission per year, we must describe a technology roadmap in which $1x10^{22}$ antiprotons/year, or 17 mg/year, can be produced within 20 years. This represents a production increase factor of $2x10^{7}$.

As described in the previous progress report, Hbar Technologies has developed a plan for increasing the Fermilab antiproton production rate by a factor of 1000x by using recirculating protons passing through a thin production target [6]. By also increasing the number of proton bunches and the proton intensity per bunch, another factor of 10x can also be envisioned within the same general accelerator complex. As shown on figure 3, we estimate that these additions and modifications to the Fermilab accelerator complex could be ready in 2010.

This leaves an additional factor of 1000x to reach the antiproton production rate needed for supplying one deep-space mission per year. If one assumes the same 1.3 year doubling time found in the historical production rate increases, the time required to achieve this additional factor of 1000x is 9 years. Therefore, a 20 year timeline for growth in antiproton production rate is conceivable. The individual factors that may lead to this thousand fold increase are building more facilities (10-30x), parallel antiproton capture/deceleration systems to increase the momentum bandwidth (2-3x), and the use of higher intensity accelerators for proton injection (10-30x).

In general, we can summarize future production levels roughly as follows:
1) current production is a ng/yr ($5 X 10^{14}$/yr);
2) μg/yr can be achieved with upgrades to the Fermilab facility (~300 M$);
3) mg/yr are possible with a new dedicated facility but using current technology (~2 B$);
4) g/yr will require advances in technology and multiple facilities.

Thus, sufficient levels of production are within the reach of this country within the next couple of decades.

Antimatter Storage

Antiprotons produced at CERN have been captured and stored in Penning Traps. The largest capacity trap for antiprotons ($1 X 10^{12}$) is the High Performance Antimatter Trap (HiPAT) built by the NASA Marshall Space Flight Center. Hipat is a cylinder with a 1 m diameter and a 1 m length and weighs around 200 kg. In order to reduce the mass and increase the capacity of a trap, we have examined an alternative storage scheme uses a purely electrostatic field and does not require the large superconducting magnets. A good deal of effort has been devoted to understanding the limitations of present electrostatic traps and developing a technology roadmap for mitigating these limitations.

Electrostatic bottles have been demonstrated by two groups with different geometries [7,8,9] (figure 8). The purpose of these particle containers is physics research. Therefore, the vacuum pressure, electrostatic field uniformity, and power supply regulation specifications are consistent with their need to store particles for seconds or minutes. Additionally, these containers are bulky and not all portable.

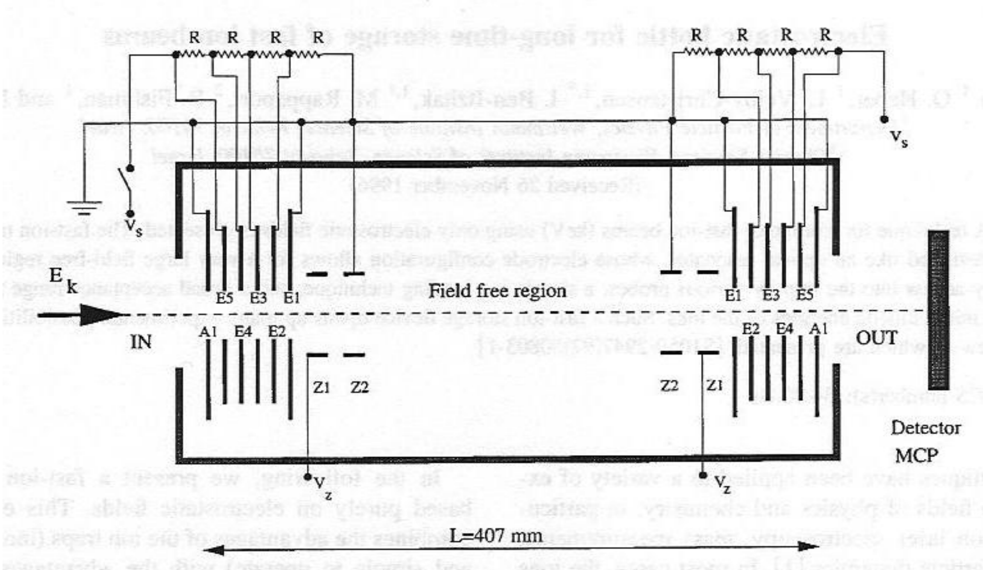


Figure 8. Sketch of a more traditional electrostatic trap as depicted in reference [8].

Unfortunately, these traps are quite small and crude, nothing approaching a design which could be used for portable storage for spaceflight. On the other hand, the aerospace implications of these revolutionary new trap designs are stunning. The traditional scaling relationships between storage volume and weight are now completely alleviated, and one can conceive of traps with orders of magnitude more volume that weigh well less than 1 kg.

The development of a light weight, high capacity storage unit will allow the production of antihydrogen to be pursued. A research group at CERN (ATHENA) recently announced the verified formation of low-temperature antihydrogen atoms [10] using Penning Traps. Higher capacity traps will enable higher levels of production of antihydrogen.

The next step is to demonstrate the ability to hold the neutral antihydrogen atoms in an Ioffe-Pritchard trap. This trap utilizes a magnetic field gradient to couple to the magnetic moment of the antihydrogen atom. If the antihydrogen atoms can be constrained for sufficient times, the formation of antihydrogen molecules may be demonstrated.

Condensation of normal hydrogen molecules into solid hydrogen (SH2) pellets has been demonstrated in the laboratory [4]. The behavior and properties of SH2 has been thoroughly studied by researchers in Japan [3]. Disks of solid hydrogen have been used at KEK as targets for particle beam experiments. Thus, evaporation rate of SH2 has been experimentally determined.

Current physics theories predict that solid antihydrogen should behave exactly as normal SH2. Thus, the production of antihydrogen molecules should enable the formation of solid antihydrogen (SH2bar) micro-pellets. By adding normal electrons to the SH2bar pellets, a net negative charge will be placed on the pellet due to the annihilation of the positrons in the SH2bar. By demonstrating the ability to hold a charged micro-particle in a low-mass electrostatic trap, the final step toward a high-capacity antihydrogen storage system will be shown.

This will enable the antimatter sail concept.

Conclusion

The antimatter driven sail concept continues to appear both feasible and attractive for deep space missions. System studies indicate that around thirty milligrams of antimatter could take a 135 kg platform to 250 AU within 10 years. A key development that enables this performance is the creation of a new power conversion system with a very low specific mass, less than 15 kg/kW. A key assumption in our calculations is the momentum delivered to the sail due to antimatter induced fission. We are still investigating critical elements of the concept. However, our preliminary findings indicate that if antimatter can be produced in quantities of milligrams per year and stored as macroscopic pellets of antihydrogen, then humanity could send a probe to study real interstellar space. This same technology may even allow a mission to the next star.

Bibliography

1. Deutsch, L.J., Salvo, C., and Woerner, D., “NASA’s X2000 Program – an Institutional Approach to Enabling Smaller Spacecraft,” http://klabs.org/DEI/Processor/X2000/99-0049.pdf

2. Hemmati, H. and Lesh, J.R., “A Combined Laser-communication and Imager for Microspacecraft, (ACLAIM),” http://lasers.jpl.nasa.gov/PAPERS/ACLAIM/aclaim.pdf

3. http://psux1.kek.jp/~benkeh2t/SHT/sh2t.html - solid hydrogen targets and properties.

4. Palaszewski, Bryan, “Solid Hydrogen Experiments for Atomic Propellants,” AIAA Paper 2000-3855, 2000.

5. http://nssdc.gsfc.nasa.gov/planetary/voyager.html - Voyager characteristics

6. N. Mokhov and A.VanGinneken, “Increasing Antiproton Yields Via Recirculating Beam Targeting”, Internal Fermilab technical memo FN-621, 1994.

7. S.P. Moeller, “ELISA, An Electrostatic Storage Ring for Atomic Physics”, Nucl. Instrum. Meth. in Phys. Res., A394, pp. 281-286, 1997.

8. D. Zajfman, et. al., “Electrostatic Bottle for Long-Time Storage of Fast Ion Beams”, Phys. Rev. A, Vol. 55, No. 3, pp. R1577-80, 1997.

9. H.T. Schmidt, H. Cederquist, J. Jensen, A. Fardi, “Conetrap: A Compact Electrostatic ion Trap”, Nucl. Inst. Meth. in Phys. Res., B173, pp. 523-527, 2001.

10. Amoretti, M., et. al., “Production and detection of cold antihydrogen atoms,” Letters to Nature, Sept. 18, 2002.