RF Stabilization for Storage of Antiprotons

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Abstract. Portable storage of antimatter is an important step in the experimental exploration of antimatter in propulsion applications. The High Performance Antiproton Trap (HiPAT) at NASA Marshall Space Flight Center is a Penning-Malmberg ion trap being developed to trap and store low energy antiprotons for a period of weeks. The antiprotons can then be transported for use in experiments. HiPAT is being developed and evaluated using normal matter, before an attempt is made to store and transport antiprotons. Stored ions have inherent instabilities that limit the storage lifetime. RF stabilization at cyclotron resonance frequencies is demonstrated over a period of 6 days for normal matter ion clouds. A variety of particles have been stored, including protons, C^+ ions, and H_2^+ ions. Cyclotron resonance frequencies are defined and experimental evidence presented to demonstrate excitation of cyclotron waves in the plasma for all three species of ions.

INTRODUCTION

Matter/antimatter annihilation is the highest energy density material known. The chemical energy stored in one Shuttle External Tank is equivalent to the annihilation energy of 42 mg of antiprotons. If stored in the form of antihydrogen, this mass would occupy 0.026 cc of volume. This energy density makes antimatter an attractive area of research for space propulsion.

The primary application of antimatter technology for space exploration is for use in a propulsion system, taking advantage of the high energy density to decrease propulsion system mass, and the high energy particles for substantial Isp. A variety of concepts have been proposed on paper, with estimates of Isp from 10^3 to 10^7 seconds (Morgan, 1982, Kammash, 1992, Gaidos, 1998). The experimental investigation of these concepts is the primary need for antimatter propulsion research.

There are also potential defense and commercial applications of antimatter technology. Improvements in production and portable storage lead to possible uses in nuclear medicine (Lewis, 1997), including improved cancer radiation therapy, production of medical isotopes, etc. Use of antimatter annihilation products for material assay for both quality control and security are also possible. As an example, π mesons generated by antiproton annihilation may be used to probe smuggled shielded nuclear materials. Several commercial companies have formed to research these possibilities, relying on both private and government funding. These technologies may also find science applications in space exploration.

To successfully use antimatter for propulsion, three main areas must be addressed; portable storage of antimatter (Holzscheiter, 1996), use of antimatter to produce thrust and high quantity production of antimatter. Due to the high cost of producing antimatter (Rider, 1997, Schmidt, 2000) and the difficulty of storage, propulsion concepts that use antimatter to initiate fission (Gaidos, 1998), or possibly even fusion (Perkins, 1999, Smith, 1995), are likely the nearest term potential antimatter propulsion technologies.

The state-of-the-art in storage and transport is nearly ready for initial storage and transport of antiprotons to an experiment facility. Production is currently enough to perform proof-of-principle experiments on hybrid antimatter propulsion concepts.

CP746, *Space Technology and Applications International Forum—STAIF 2005,* edited by M. S. El-Genk

Near term storage is being addressed at MSFC with the High Performance Antiproton Trap (HiPAT). HiPAT is a portable Penning-Malmberg ion trap that stores ions as a non-neutral plasma (Martin, 2001). Design capacity is 10^{12} antiprotons (approximately one half day's production at Fermilab) with a storage lifetime of ~18 days. Testing and development of HiPAT are ongoing using normal matter (Martin 2002, 2003). The next step is to transport HiPAT to Fermilab to begin trapping and storage tests with antiprotons. Following successful trapping and storage, a specially constructed semi-trailer will be built with appropriate power and shielding, and transportation tests will be conducted. Successful transportation of stored antiprotons will enable propulsion concept tests to be performed at MSFC or other appropriate sites. This paper documents the successful extension of storage life for protons to a period of six days, with no noticeable loss of particles. This extended storage lifetime is accomplished through the use of cyclotron compression of the ion plasma.

HiPAT DESCRIPTION

The purpose of HiPAT is to develop a portable ion trap that would allow capture, storage and transport of antiprotons from a production facility to an experiment facility. The development work is being done using a proton beam to simulate the antiproton beam. This allows the development work to be done with normal matter, avoiding the cost and complexity associated with use of antiprotons. The HiPAT experiment is a Penning-Malmberg trap that stores ions as a non-neutral plasma. It consists of a 4 T superconducting magnet system, high voltage electrode structure, beamline and ion source. Figure 1 is a layout of the HiPAT experiment, showing the magnet system, electrodes and pump hardware. The ion beam source and beamline are not shown, but lie to the right side of the figure. The connection of the trap to the ion source is made through a beamline with a series of differential pump stations and beam optics. An electron beam in the beamline near the trap was initially used to ionize background gas to fill the trap, but will be used to add electrons to the trap before antiproton trapping to allow electron cooling of the antiprotons.

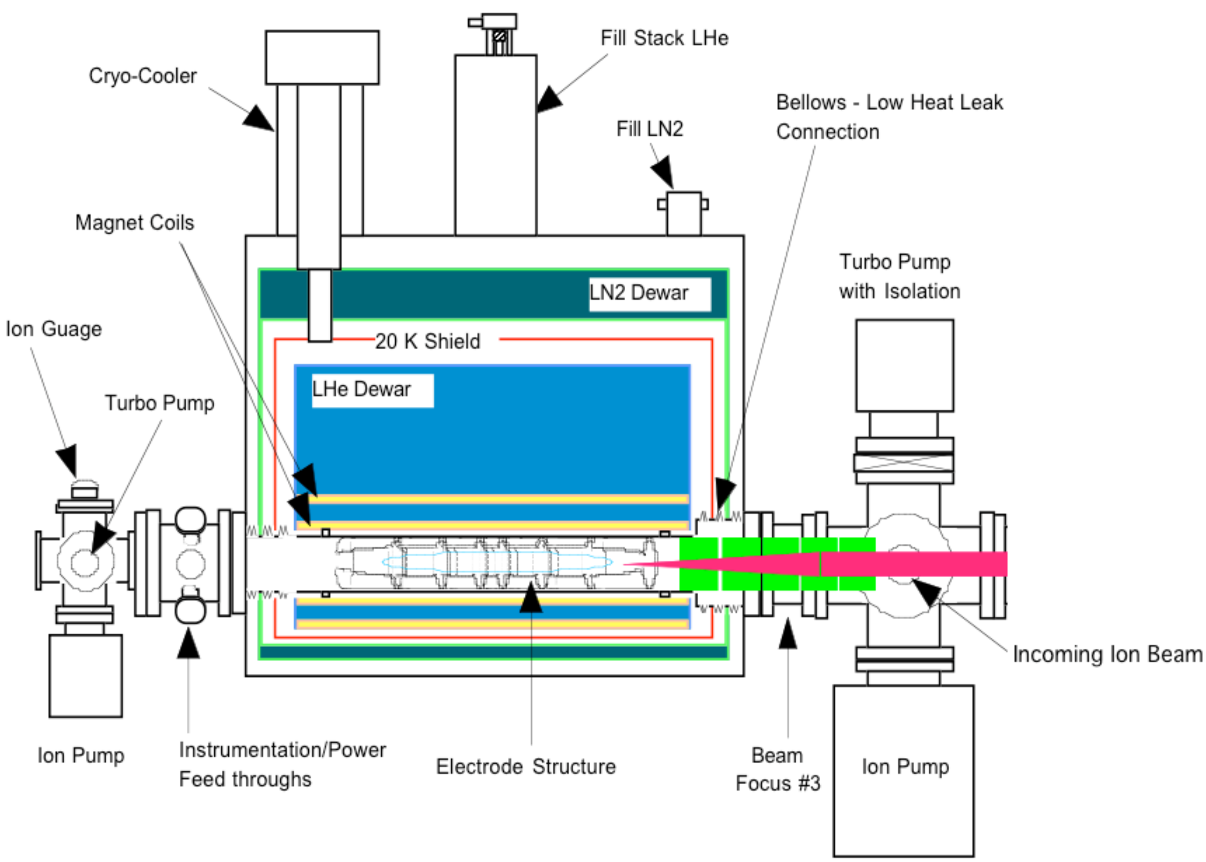

FIGURE 1. Layout of the HiPAT Experiment.

Figure 2 shows the internal electrode structure that makes up the heart of the Penning-Malmberg trap. The electrodes are hollow cylinders that are given a DC voltage to form an axial potential well. This provides the axial confinement of the ions. In addition to the electrodes pictured in Figure 2, there is a thin circular electrode to the left of E6, called the rear spoiler, that caps the trap at that end. There is also a thin (1/8") plate front spoiler just to the right of electrode 6 that reduces the entrance diameter by half, helping to close the potential well. The magnetic field runs axially, and provides radial confinement of the charged ions. Electrodes E3 and E4 are segmented azimuthally, with four 90˚ segments each (labeled A, B, C and D). This allows a rotating electrical field perturbation to be added to the potential well and used in the trap for manipulating the plasma. Waves in the plasma can be generated by application of RF perturbations on the DC bias when the RF frequency coincides with a plasma mode. Oscillations and waves in the plasma can likewise be detected by 'listening' to the RF perturbations induced on other electrodes. A spectrum analyzer is used as an RF source on one electrode to sweep a range of frequencies, and another electrode is used as the receiving antenna. The resulting spectrum shows a marked increase in transmission strength at frequencies where a plasma mode is excited.

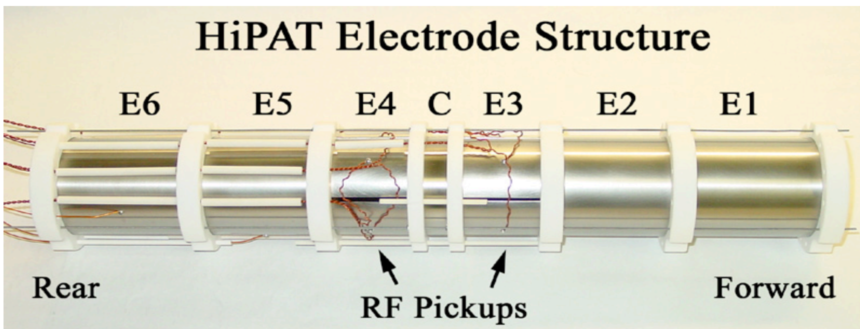

FIGURE 2. Electrode Structure Inside HiPAT (E3 and E4 are Made of Four 90˚ Azimuthal Segments).

Some azimuthal modes in the plasma can be used to compress the plasma radially . These modes are being explored as methods of increasing storage lifetime of protons (and antiprotons) indefinitely in the trap. Various experimenters (Hollman 2000, Greaves, 2000) have been successful in trapping ions indefinitely by using the rotation frequency of a short plasma column. Increased lifetime and centering of ions using the cyclotron frequency has been demonstrated for both plasma columns (Sarid, 1995) and for harmonic traps (Bollen, 1996).

CYCLOTRON WAVES IN NON-NEUTRAL PLASMAS

The plasma frequency we are concerned with in this experiment is actually the modified cyclotron frequency, ω_+. References to cyclotron frequency in Penning traps are often to this modified cyclotron frequency. This frequency is a modification of the ideal, single charged particle motion in a uniform magnetic field, the cyclotron frequency, ω_c=qB/m, with q being the electric charge, B the magnetic field and m the mass of the ion. The motion is modified by the imposition of electric potential gradients on the charged particle, causing **E**x**B** forces. In a Penning-Malmberg trap, these gradients are caused by radial electric fields in the potential well (Brown 1986), and by the space charge of the plasma itself (Davidson, 1974). The radial electric fields of the trap are tied to the axial potential, and can be related to the axial frequency of the trap, $\omega_z=A_g(qV_T/m)^{1/2}$, where A_g is a geometry factor specific to the trap, and V_T is the potential depth of the well. The radial electric fields of the plasma itself are tied to the density of the plasma, and can be expressed in terms of the plasma frequency, $\omega_p=(q^2n_o/\varepsilon_o m)^{1/2}$, where n_o is the plasma density, and ε_o the permittivity of free space. The result of these forces on the plasma is the following expression of two fundamental frequencies, ω_+ and ω_-, in a Penning-Malmberg trap.

$$\omega_\pm = \frac{\omega_c}{2} \pm \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2} - \frac{\omega_p^2}{2}} \qquad (1)$$

ω_- is referred to as the magnetron frequency. Note that the relationship $\omega_c=\omega_++\omega_-$ also follows from equation 1. For low densities, the ω_p term, the space charge and collective effects are negligible, and the ions are no longer considered a plasma, but can be treated as single particles. In flat, or plasma column traps (with a uniform potential at the floor of the well), the ω_z term is negligible.

CYCLOTRON WAVES OF H^+ IONS

Protons from the ion beam were captured in HiPAT using a deep potential well with voltages of 3000, 1950, 1900, 300, 102, 300, 1900, 3000, and 3300 V on the rear spoiler, E6, E5, E4, C, E3, E2, E1, and front spoiler, respectively. The magnetic field was set at 4 T. The cyclotron frequency of protons with this field is ω_c=60.99 MHz This cloud was maintained for six days by use of cyclotron compression. The spectrum analyzer was used to sweep from 60-61 MHz around the cyclotron frequency, at a strength of -20 dBm. This results in a pulsed compression of the plasma, as the frequency is near the cyclotron frequency for only a small portion of the sweep. The signal was transmitted through a balun (for 180˚ phase splitting) to electrode 3 on two opposing segments (E3B and E3D). The pickup electrodes were two opposing segments of electrode 4 (E4A and E4C), combined through a balun. Pickup on two opposing segments, with signals added 180˚ out of phase ensures that only azimuthal plasma modes are detected. Figure 3 shows a snapshot of the cyclotron wave set up in the plasma on the day of injection. Note that the peak frequency is 60.49 MHz, 500 kHz below the true cyclotron frequency.

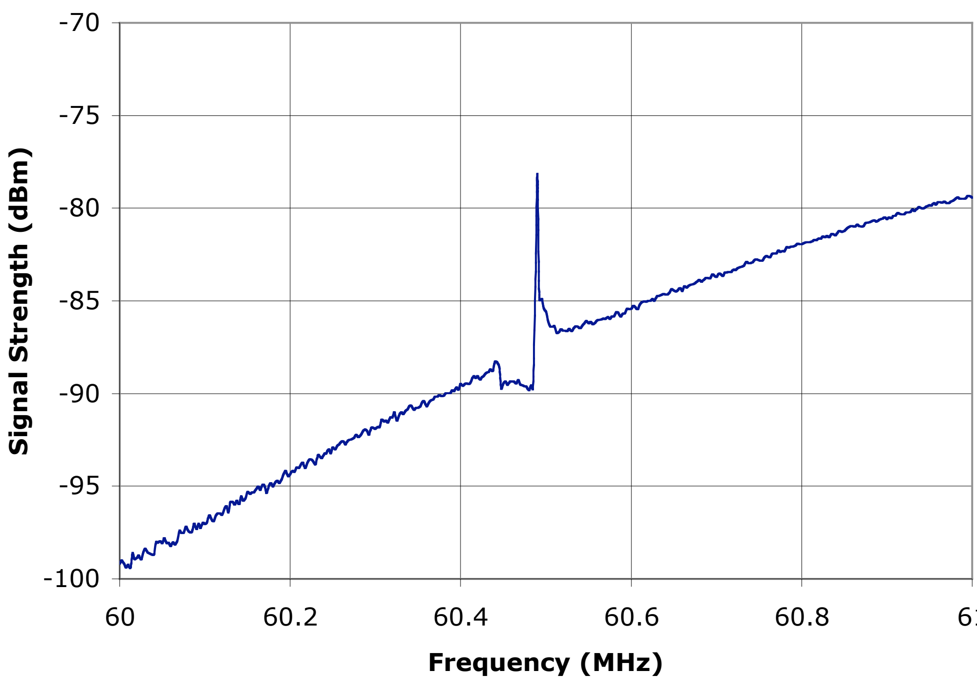

FIGURE 3. H^+ Cyclotron Signal After Injection on Day 1.

The magnetic field was changed on Day 1 of the storage to confirm that the mode frequency changed with magnetic field. ω_c scales with B, and ω_+ scales with B when $\omega_c^2 >> (\omega_z^2+\omega_p^2)$. Figure 4a shows the change in ω_+ with a slight change in B. The ratio of ω_{+2}/ω_{+1} is 0.99862, and the ratio of B_2/B_1 is 0.99867, confirming (within the accuracy of the measurements) the scaling with B. On Day 2 of the storage the magnetic field strength was varied as low as 1.07 T, though below 1.6 T the plasma did not stabilize to a steady state equilibrium and began to appear unstable (as evidenced by erratic shifts of ω_+). The magnet was kept above 1.6 T for the rest of the storage period.

Figure 4b is typical of the results at various magnetic field strengths. The field in Figure 4b is at 2.133 T, with a pure cyclotron frequency of ω_c=32.528 MHz, 330 kHz above the modified cyclotron frequency. Compared to the full 4 T field, the ratio of ω_{+2}/ω_{+1} is 0.533, and the ratio of B_2/B_1 is 0.532. Note that other signals appear in Figure

4b. These signals are believed to be sidebands due to some linear combination of azimuthal modes. These sidebands have not been identified.

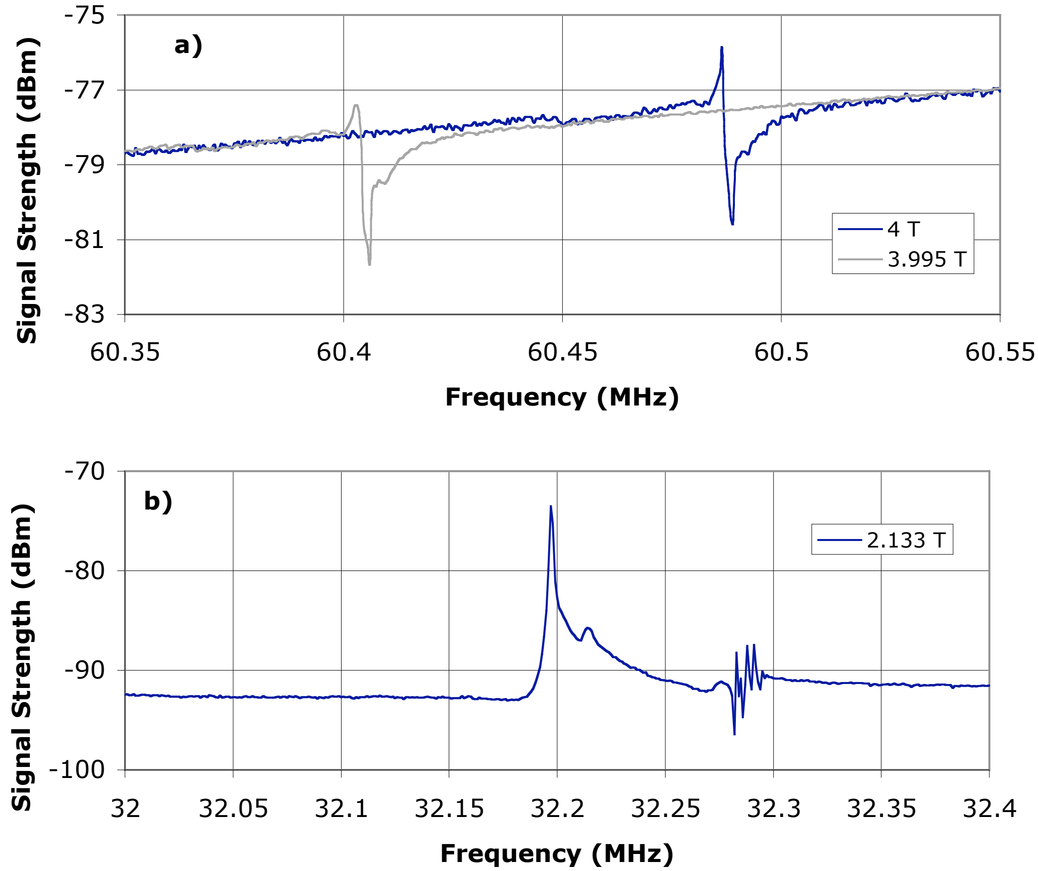

FIGURE 4. Change in Modified Cyclotron Frequency With Change in Magnetic Field Strength

Similar testing continued throughout the storage, with changes in magnetic field strength, RF drive strength, frequency etc. Cyclotron drive was continued throughout each night. On Day 6 of the ion storage there was a failure of the magnet controller, and the plasma was lost. Up through Day 6, there was no sign of the plasma permanently losing particles or changing shape. As conditions were changed, the plasma would take a few minutes to reach equilibrium, but would repeatably return to the same equilibrium state under the same conditions. The conclusion, implied from Equation 1 is that the plasma density and species must remain constant for the modified cyclotron frequency to remain constant.

EVIDENCE OF MULTIPLE SPECIES

Charge exchange of protons with background gas has been a major problem in storage of protons in HiPAT. The electron affinity of protons is such that the cross-section for charge exchange with background neutrals is high. A search of cyclotron frequencies was made to determine what species in the plasma would respond to cyclotron drive. Two additional species were detected by exciting cyclotron waves, C^+ and H_2^+. Figure 5 shows evidence of plasma waves induced in both these species. Figure 5a demonstrates the change of frequency with magnetic field for H_2^+ ions, consistent with results for H^+ in the previous section. These signals are very weak, and the peaks are 'split'. The split peaks may be evidence of a sideband, similar to Figure 4. Figure 5b is a strong signal at the frequency for C^+. Other frequencies are also evident here, that are most likely sidebands or possibly other azimuthal modes. Note the large difference in signal strength between the species. It has been demonstrated that signal strength is not a reliable measure of species concentration (Sarid, 1995). This is further complicated by a wide range of electronics bandwidths, baluns and amplifiers necessary to collect the data presented.

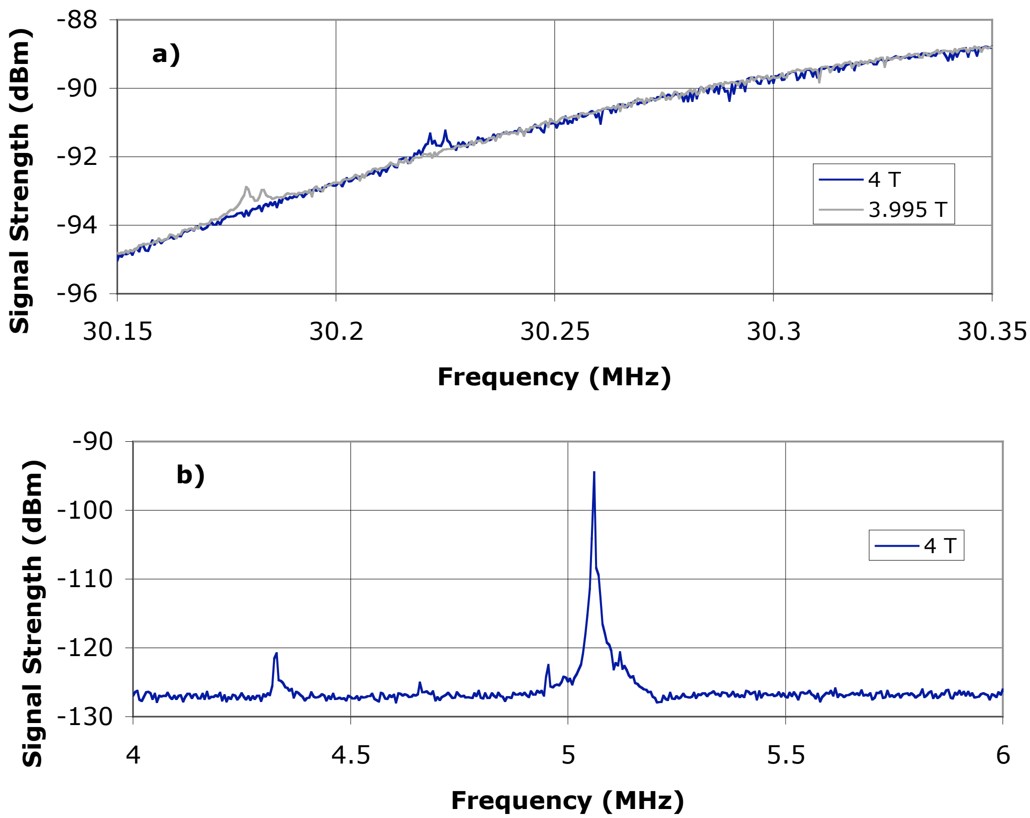

FIGURE 5. a) ω_+ at Two Magnetic Field Strengths for H_2^+ Ions; b) ω_+ for C^+ Ions.

The presence of multiple species due to charge exchange with background neutrals is one of the major challenges faced in the development of HiPAT. This is due to the choice to use protons for the initial development work. Antiprotons, while presenting their own challenges, do not charge exchange with the background.

CONCLUSIONS

Cyclotron stabilization of protons in HiPAT appears to be very successful. A six day storage life has been demonstrated, with no measurable loss of ions. This is one third of the design storage lifetime of 18 days. Although this appears very promising, some work still needs to be done to verify that the ions initially injected into HiPAT are the same that are present at later times during the storage, i.e. no ion replenishment occurs such as background ionization. Continued work in this direction could include attempts to store other ions that are less prone to charge exchange. Further diagnostics are also being developed to determine the number of ions, radial density distribution and plasma temperature, to more fully characterize the behavior of ions in HiPAT.

ACKNOWLEDGMENTS

The authors wish to acknowledge the support of the Propulsion Research Center at NASA Marshall Space Flight Center for funding this work. The contributions of Jim Martin, Herb Sims and Gene Fant at MSFC, as well as advice from Francois Anderegg and Fred Driscoll from the University of California San Diego are also greatly appreciated.

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