Overview of The High Performance Antiproton Trap (HiPAT) Experiment

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11-14-2002

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The annihilation of antiprotons with protons represents the highest energy density of any known reaction $10^8 \text{ MJ/g}$: the ultimate form of stored energy for future high specific impulse deep space missions.

- 42 mg of antiprotons = energy of 750,000 kg fuel/oxidizer on the Space Shuttle ET
- Envisioned antimatter initiated propulsion concepts require 0.1 to 10 micrograms of antiprotons.
- Storage is a key enabling technology required by all users of antiprotons (NASA and commercial).
- Current production sufficient to evaluate basic handling/utilization technologies.
Matter/Antimatter annihilation represents the “ultimate” source of stored energy for space propulsion

- The potential benefits to propulsion suggest a phased low level research program.
- Research activities focused on the basic technologies are required to assess its potential.
- Existing antiproton production facilities provide levels sufficient for proof of concept research.
- Results of these assessments can be used to determine further investment.

Antiproton storage is a fundamental technology required to experimentally assess utilization methods. The HiPAT device provides a critical resource to the research community supporting basic evaluation

- Knowledge in the operations required for the basic handling and manipulation of antiprotons.
- Development of techniques and basic insight into the operation at production facilities.
- Provides an accumulator enabling single shot experimental testing of propulsion concepts.
- Serves as a front end to research related to high density storage of antimatter.

The HiPAT provides an asset to commercial based enterprises

- Support of research in the medical field related to the development of radio isotopes production and tumor treatment techniques.
To address the storage issue, a test device termed the High Performance Antiproton Trap (HiPAT) has been designed and fabricated.

- Electromagnetic Penning-Malmberg design
- Capacity of up to $1 \times 10^{12}$ antiprotons
- Storage lifetimes of 18 days or more
- Ultra high vacuum system ($<10^{-11}$ torr)
- Capable of portable operation
- RF stabilization and passive particle detection
Beam Line, Ion Source, and Superconducting Magnet Hardware

- Designed around an ultra high vacuum system with differential pumping capability (maintains 6 orders of magnitude between trap and ion sources).
- Vacuum level (10^{-12} torr range) reduces loss by radial diffusion and annihilation.
- LHe/LN\textsubscript{2} cooled 4 Tesla superconducting magnet system (end compensated solenoid).
- Hydrogen ion source and hot filament electron gun provide "normal matter" ions.
- High voltage electrostatic beam optics (Einzellens) to guide and focus ion beams.
The containment zone — located in the bore of the superconductor — is surrounded by a series of electrodes and insulator segments. The $10^{12}$ particles are confined radially by the magnetic field and axially by the electric field.

- Magnetic field of 1 Tesla required to balance cloud’s radial space charge.
- Electric field of 20 kV required to balance the cloud’s axial potential.

\[
N_{\text{Brillouin}} = \frac{B^2}{2\mu_0 Mc^2}
\]

\[
V_{\text{radius}} = \frac{nq}{4\pi\varepsilon_0 R}
\]
Laboratory Operations

- **Cleaning techniques on the UHV system**
  - Hydrogen glow discharge cleaning (GDC), Titanium sublimation pumps (TSP).
  - Achieve very low vacuum to minimize diffusion loss and ion chemistry/charge exchange.

- **Ion production within the containment volume via beam ionization**
  - Simplistic operation using electron and ion beams to generate ions in place.
  - No cycling of electric fields required.

- **Dynamic Capture of externally produced ions**
  - Precision timing of beam line valves, focusing lens and trap electrodes.
  - More closely simulates anticipated operation at antiproton production site.

- **Radio Frequency Systems.**
  - Development of and experiments with particle detection and stabilization techniques.
Effort focused on reducing “contaminants” in the vacuum system (e.g., carbon compounds et.al.).

- Minimize charge exchange, preserve hydrogen.
- Increase maximum operating voltage (because of reducing potential for spontaneous glow discharge).

Hydrogen glow discharge techniques to scrub vacuum system.
- DC power up to 500 watts.
- RF power up to 100 watts.
- Thermal bake out average 250 °C

Result
- Current pressure 7.2x10-12 torr — factor of 20 improvement over previous tests.
- Glow discharge threshold raised from 2 to 10 kV: visible glow virtually eliminated up to 20 kV.
- Atm to 10-12 torr — less than a week.
Ion Production Via Electron Gun

Simple ionization techniques provide straightforward mechanisms to investigate lifetimes and assess RF systems. An electron (or ion) beam can produce trappable ions \textit{in situ}.

- Technique can be called a "poor man's" ion source
- Primary beam plows through the potential well, ionizing residual background gas (primarily $H_2$)
- Energetic (secondary/tertiary/...) electrons and ions also ionize background gas
- Total = primary ionization + (e$^{-}$ & ions)$_{2nd}$ + (e$^{-}$ & ions)$_{3rd}$ + ...

$$
\begin{align*}
e^- + H_2 & \rightarrow H + H^+ + 2e^- \\
e^- + H_2 & \rightarrow H^- + H^+ + e^- \\
e^- + H_2 & \rightarrow e^- + e^- + H_2^+
\end{align*}
$$

- Probability of formation based on:
  - Background density: $n \ (\sim 1 \times 10^6 \ \text{cc})$
  - Cross section: $\sigma \ (\sim 1 \times 10^{-16} \ \text{cm}^2)$
  - Path length $L \ (\sim 25 \ \text{cm})$ (single pass)

$$
e_{total} = \frac{I_{gun} \ t_{gun}}{1.6 \times 10^{-19}}
$$

$$
\text{Ions}_{total} = n e_{total} \sigma L_{path}
$$
Demonstrate Quantity and Lifetime of Trapped Ions Using "Normal Matter" Hydrogen Ions (H\(^{+}\)) to Simulate Antiprotons.

- NEC source system for ion generation to more closely simulate actual antiproton loading technique.
- Single species ions created externally and transported along beam line to the trap system.
- Source large neutral gas loads require dynamic cycling of isolation valves and differential pumping.
Transport ion beams from the NEC RF/SNICS sources to the trap system

- Distance of approximately 3 meters requires use of Einzel electrostatic focusing lens
- Two beam line apertures <1cm diameter (differential pumping)
- Compensation against the earth’s magnetic field (0.5 gauss)
- Focus to align ions with magnet’s fringe field (maximize particle acceptance)
- Movable beam detectors used to fine tune voltages on Einzel lens
Only a limited number of ions can be captured from a single beam spill. Reaching higher fill levels necessitates stacking, which entails the following:

- Rapid cycling of electrode groups between a full and reduced electric field condition
- Time must be allowed for hot ions to cool, preventing their escape on the next cycle

**Six Segment Electrode Structure with Electric Potential**

1. Ion Beam Introduced Electrodes 1, 2 & 3 Grounded
2. Electrodes 1, 2 & 3 Raised Portion of Hot Beam Confined
3. Time allowed for Ions to Cool
4. Ion Beam Introduced Electrodes 1 at Reduced Potential
5. Electrodes 1, 2 & 3 Raised 2nd Portion of Hot Beam Confined
6. Time allowed for 2nd Group of Ions to Cool
The HiPAT hardware uses the following dynamic system incorporating a series of valves, electrostatic lenses, and "trap door" electrodes.
Dynamic Capture of $H^+$ Ions

The beam line connecting the ion sources to HiPAT has been configured for providing pulses of hydrogen ions. These pulses are captured by dynamically cycling the HiPAT trap.

- Beam line valves used to minimize gas loading... $10^{-6}$ torr to $10^{-11}$ torr (cycle time $\sim 2.5$ seconds)
- Focusing Einzel lens used as an electrostatic shutter. Triggering between Stall/Focus (cycle time as fast as 0.1 nanoseconds)
- Trap's forward electrode ($E_1$) voltage collapses using dump timing circuit to capture a portion of the beam. (cycle time as fast as 0.1 microseconds)
- BNC 555 pulse timer used to synchronize timing of components. Behlke high speed HTS-301 transistor switches used.
HiPAT dynamic capture system has successfully demonstrated confinement of hydrogen ions.

- Trap electrode (E1) cycle delayed varied with respect to initial ion transmission down beam line (stall/focus lens).
- Ion capture occurs only during interval where electrode cycling and the beam coincide.
- Results show \( \sim 1.5 \times 10^8 \) ions captured during the center of the interval. Leading and trailing edges of ion beam sampling not sharp due to resistance/capacitance of pickup system.
- Data shows no appreciable ionization created by incoming ion beam (no ions extracted with small delay).
- Ionization of "Hot" captured beam while it cools still to be assessed.

- Beam spill width of 4 \( \mu \text{sec} \), trap electrode cycle width of 1 \( \mu \text{sec} \).
- Trap flat potential well 1 kV (plasma column geometry) with end potentials at 3 kV.
- Ion beam set to \( \sim 2 \) kV energy with an intensity of \( \sim 20 \) \( \mu \text{amps} \).
Examine a non-destructive method for detection and diagnosis of trapped ions.

- Measure fundamental ion frequencies & amplitudes (function of containment fields).
- Apply radio frequency energy & examine the RF-to-Plasma interaction.
  - Two sets of sectioned electrodes serve as antenna for transmit and receive.
  - External low noise amplifiers, couplers, spectrum analyzer, and RF sweep generator.
  - Receiver average noise floor $-130$ dBm with 10 kHz to 100 MHz bandwidth.
- Ultimate goal: Relate signal amplitude with quantity and species, use RF energy to stabilize ions increasing lifetime from minutes to weeks.
- Product: An autonomous computer driven ion health monitoring system for HiPAT.
HiPAT electrode structure modeled

- Antenna characteristics modeled with EM circuit simulation package (Agilent HFSS)
- Preliminary topology shows that beyond 5 inches from the center the attenuation of the signal is approximately $-80$ dB (normalized to maximum power coupling) at 10 MHz
- Eventually this simulation will include coupling to the plasma.
Low frequency excitation was examined resulting in stabilization of trapped ions. Ranges of frequencies with varied amplitudes were investigated:

- Low frequency excitation 50 to 250 kHz range (cloud rotation) appears to stabilize all species.
- Frequency ranges to stabilize specific ions (while excluding others) were not found: it was an "all or nothing" proposition.
- Baseline no RF tests – nearly all ions were gone within 16 hours.
- All tests used electron gun ionization to produce trappable particles.
Closing Remarks

- The HiPAT system has been demonstrated to hold has been successfully demonstrated capture and containment of low numbers of ions.

- The NEC ion source system has provided a very nice mechanism of producing trappable ions (investigate increasing beam intensity in an effort to reduce stacking requirements).

- Focus to complete development of ion loading techniques ($10^9$ to $10^{11}$ range) with sufficient lifetime (order of minutes) to support research of the RF detection/stabilization system.

- Ongoing theoretical/experimental studies to identify plasma frequencies, densities and temperature with a goal of enabling predictable RF ion stabilization.
BACKUP STUFF

Propulsion Applications of Antimatter
Conventional antimatter driven propulsion concepts

- These systems derive all their thrust from matter/antimatter annihilation
- Large amounts of antimatter would be required for operation (grams to metric tons)
  - $I_{sp}$ = Specific Impulse (propellant usage efficiency thrust/propellant weight flow rate)
  - $\eta_p$ = Efficiency of utilization (% of available annihilation energy)
- Solid Core: Limited by material temperature issues, dense heat exchanger high conversion eff
- Gas Core: Higher temperatures achieved, low gas density results in low conversion eff
- Plasma Core: Ionized gas with magnetic confinement, very low gas density lowest conversion eff.
- Beam Core: “Ultimate” system with no secondary fluids, magnets direct annihilation products directly

<table>
<thead>
<tr>
<th>Type</th>
<th>$I_{sp}$ (sec)</th>
<th>$\eta_p$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Core</td>
<td>1,000</td>
<td>85</td>
</tr>
<tr>
<td>Gas Core</td>
<td>2,000</td>
<td>35</td>
</tr>
<tr>
<td>Plasma Core</td>
<td>$10^5$</td>
<td>10</td>
</tr>
<tr>
<td>Beam Core</td>
<td>$10^7$</td>
<td>60</td>
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Hybrid Applications

Hybrid antimatter systems are configured to derive most of their energy from fission and/or fusion reactions

- Acts as an “igniter” to initiating fission/fusion reactions lowering system driver mass requirements.
- Hybrid systems require less antimatter (1 to 100’s of μgrams) than conventional approaches.

**Antimatter-Catalyzed Micro-Fusion (ACMF)**

\[ Isp = 13,500 \text{ sec (Specific Impulse)} \]
\[ \eta_p = 15\% \text{ (Propulsive energy utilization)} \]
\[ \lambda = 0.7 \text{ (Vehicle structure/propellant mass ratio)} \]
\[ \beta = 1.6 \times 10^7 \text{ (Fusion/annihilation energy ratio)} \]

**Antimatter-Magnetically Insulated Confined Fusion (AMICF)**

\[ Isp = 200,000 \text{ sec (Specific Impulse)} \]
\[ \eta_p = 10\% \text{ (Propulsive energy utilization)} \]
\[ \lambda = 2.3 \text{ (Vehicle structure/propellant mass ratio)} \]
\[ \beta = 5.0 \times 10^3 \text{ (Fusion/annihilation energy ratio)} \]

**Antimatter-Initiated Micro-fusion (AIM)**

\[ Isp = 67,000 \text{ sec} \]
\[ \eta_p = 84\% \]
\[ \lambda = 0.2 \]
\[ \beta = 10^5 \]

\[ Isp = 61,000 \text{ sec} \]
\[ \eta_p = 69\% \]
\[ \lambda = 0.3 \]
\[ \beta = 2.2 \times 10^4 \]
Comparative performance of antimatter based propulsion concepts