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Overview of The High Performance Antiproton Trap (HiPAT) Experiment

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Why Antimatter??

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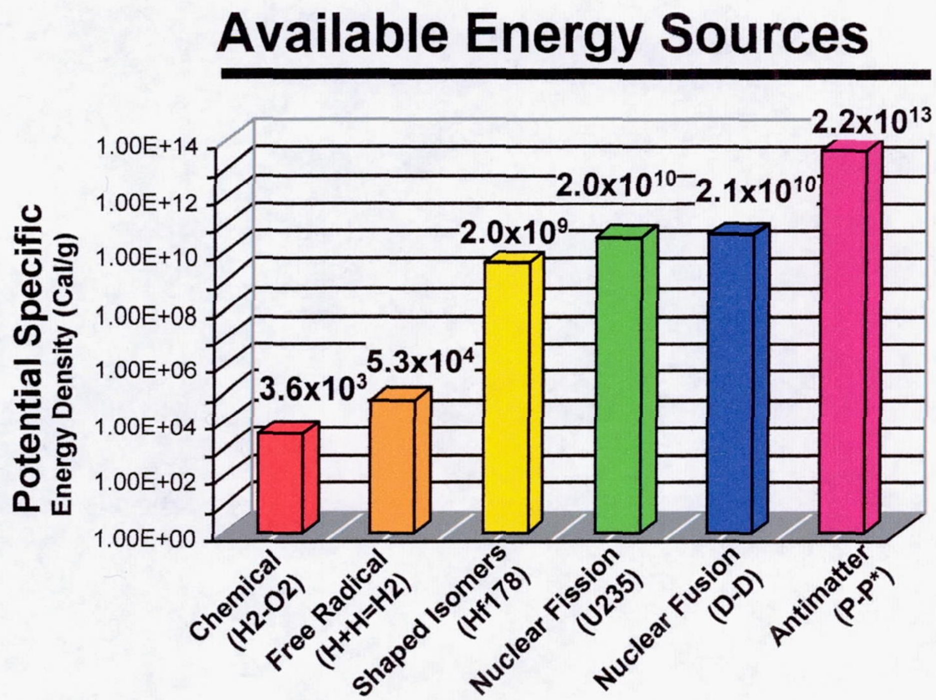
The annihilation of antiprotons with protons represents the highest energy density of any known reaction 10^8 MJ/g: the ultimate form of stored energy for future high specific impulse deep space missions.

- 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.



HiPAT Applicability

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.

Approach - Goals

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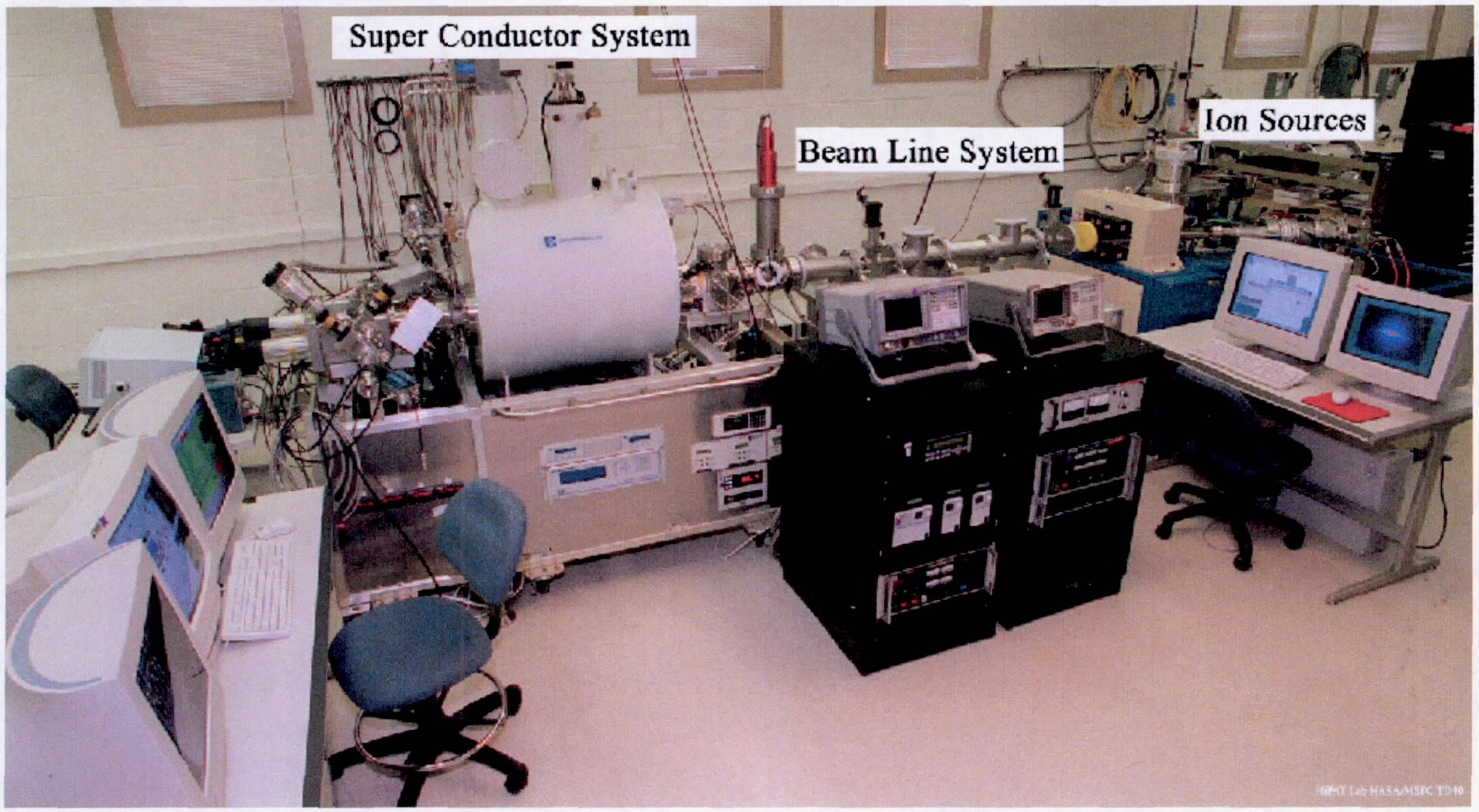
To address the storage issue, a test device termed the High Performance Antiproton Trap (HiPAT) has been designed and fabricated.

- Electromagnetic Penning-Malmberg design
- Capacity of up to 1×10^{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



HiPAT General Layout

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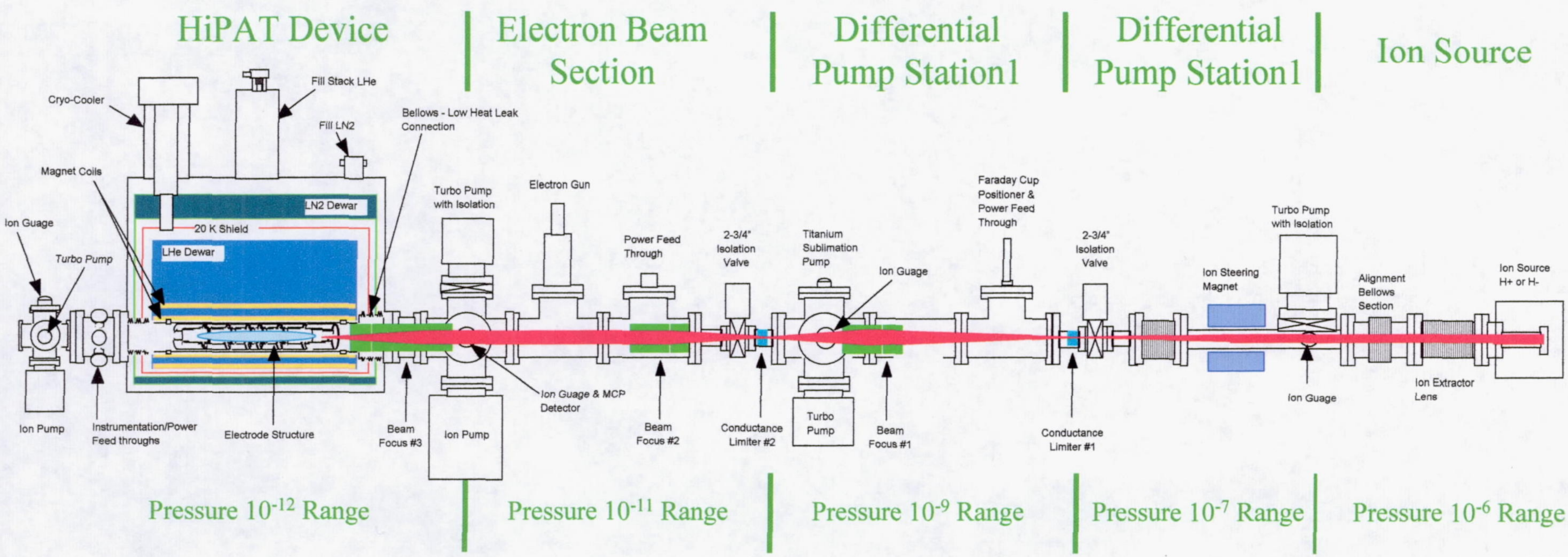
Beam Line, Ion Source, and Superconducting Magnet Hardware

- 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_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 (Einzel lens) to guide and focus ion beams.



Sizing For Containment

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.

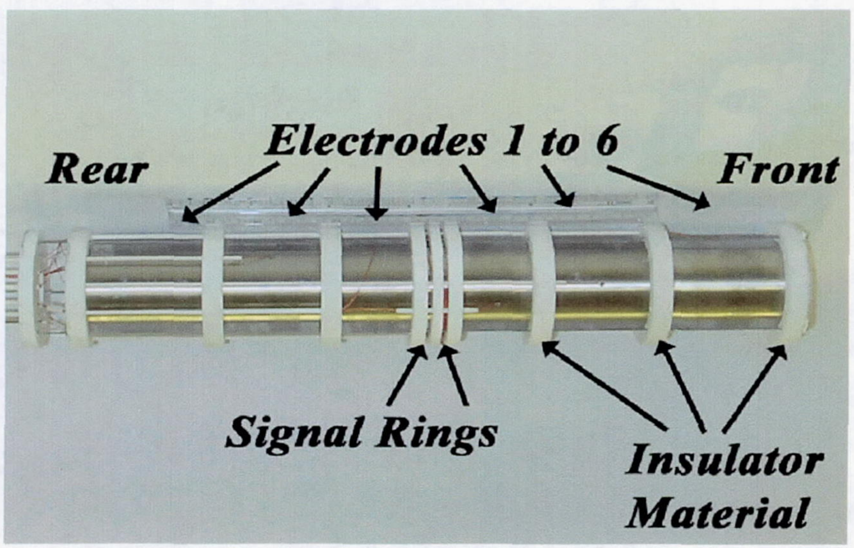
- Magnetic field of 1 Tesla required to balance cloud's radial space charge.
- Electric field of 20 kV required to balance the cloud's axial potential.

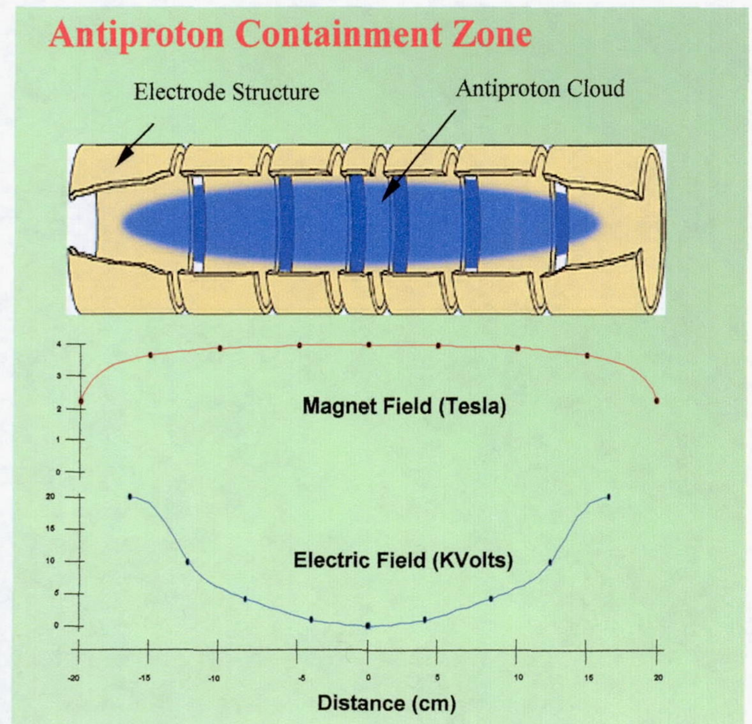
Magnetic

$$N_{Brillouin} = \frac{B^2}{2\mu_o M c^2}$$

Electrostatic

$$V_{radius} = \frac{nq}{4\pi\varepsilon_o R}$$





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.

Vacuum System Cleaning

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Effort focused on reducing "contaminants" in the vacuum system (e.g., carbon compounds et.al.).

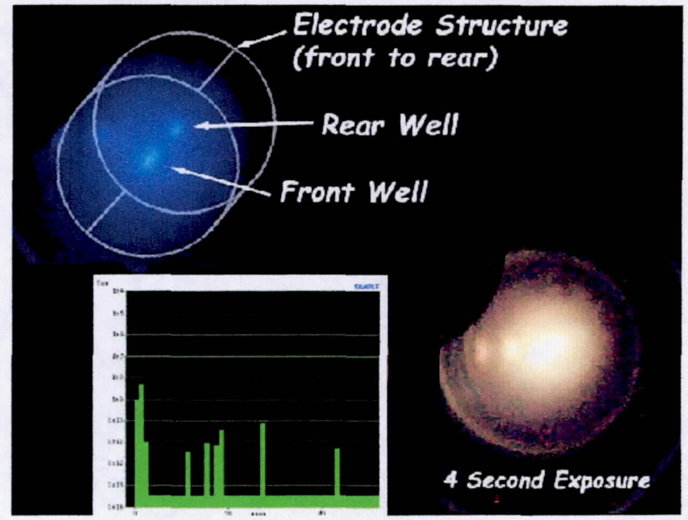
- Minimize charge exchange, preserve hydrogen.
- Increase maximum operating voltage (because of reducing potential for spontaneous glow discharge).

Hydrogen glow discharge techniques to scrub vacuum system.

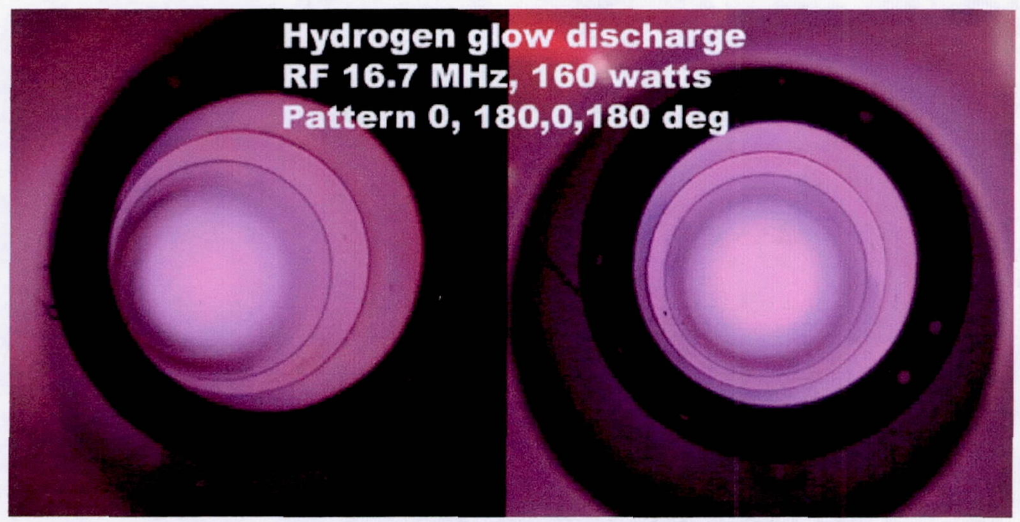
- DC power up to 500 watts.
- RF power up to 100 watts
- Thermal bake out average 250 °C

Result

- Current pressure 7.2×10^{-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.



Spontaneous Glow Discharge



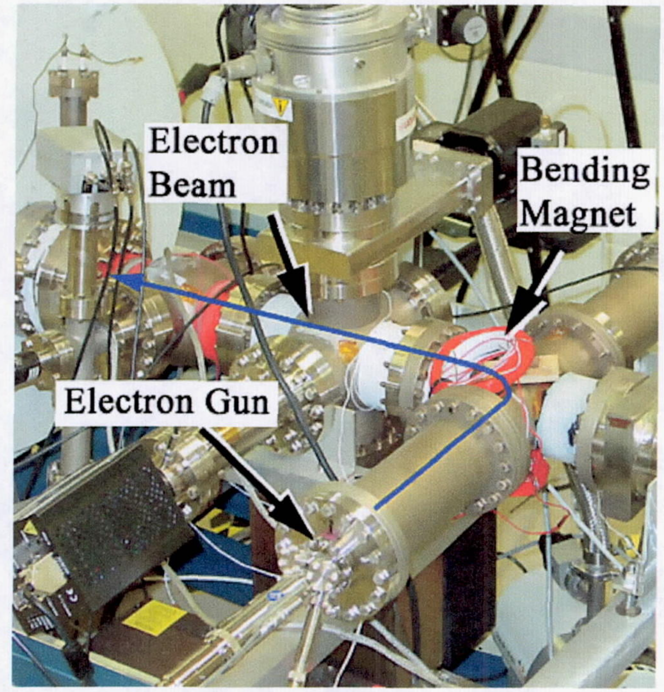
H_2 Glow Discharge Cleaning

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 *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)$_{3nd}$ + …

$$e^- + H_2 \rightarrow H + H^+ + 2e^-$$
$$e^- + H_2 \rightarrow H^- + H^+ + e^-$$
$$e^- + H_2 \rightarrow e^- + e^- + H_2^+$$



- Probability of formation based on:
  - Background density: n (~1×10^6 /cc)
  - Cross section: σ (~1×10^{-16} cm^2)
  - Path length L (~25 cm) (single pass)

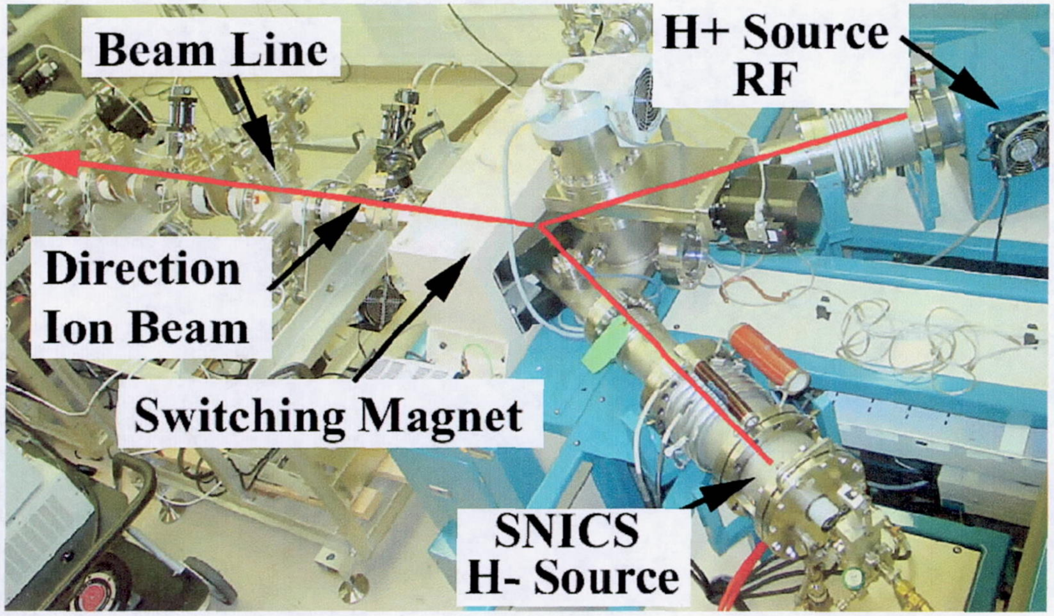
$$e_{total} = \frac{I_{gun}\, t_{gun}}{1.6\times10^{-19}}$$

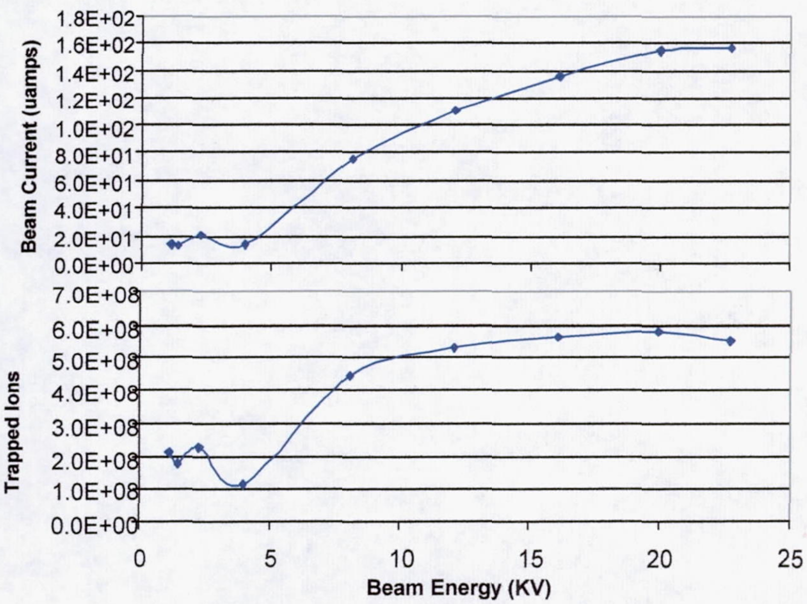
$$Ions_{total} = n e_{total} \sigma L_{path}$$

Particle Capture Via Ion Sources

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.

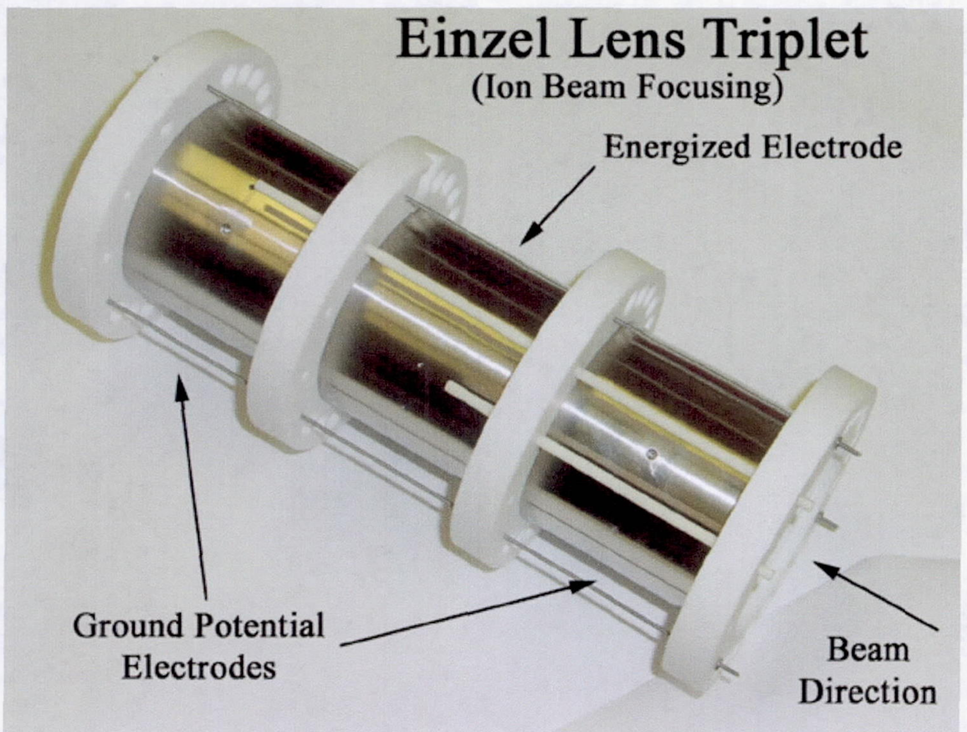


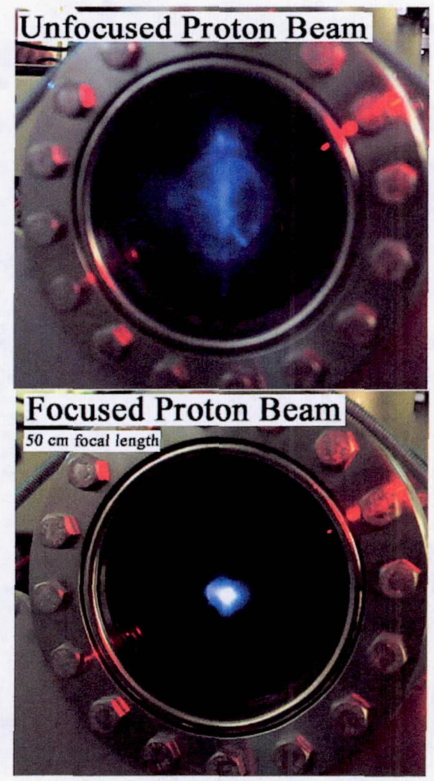


Ion Beam Steering/Focusing

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

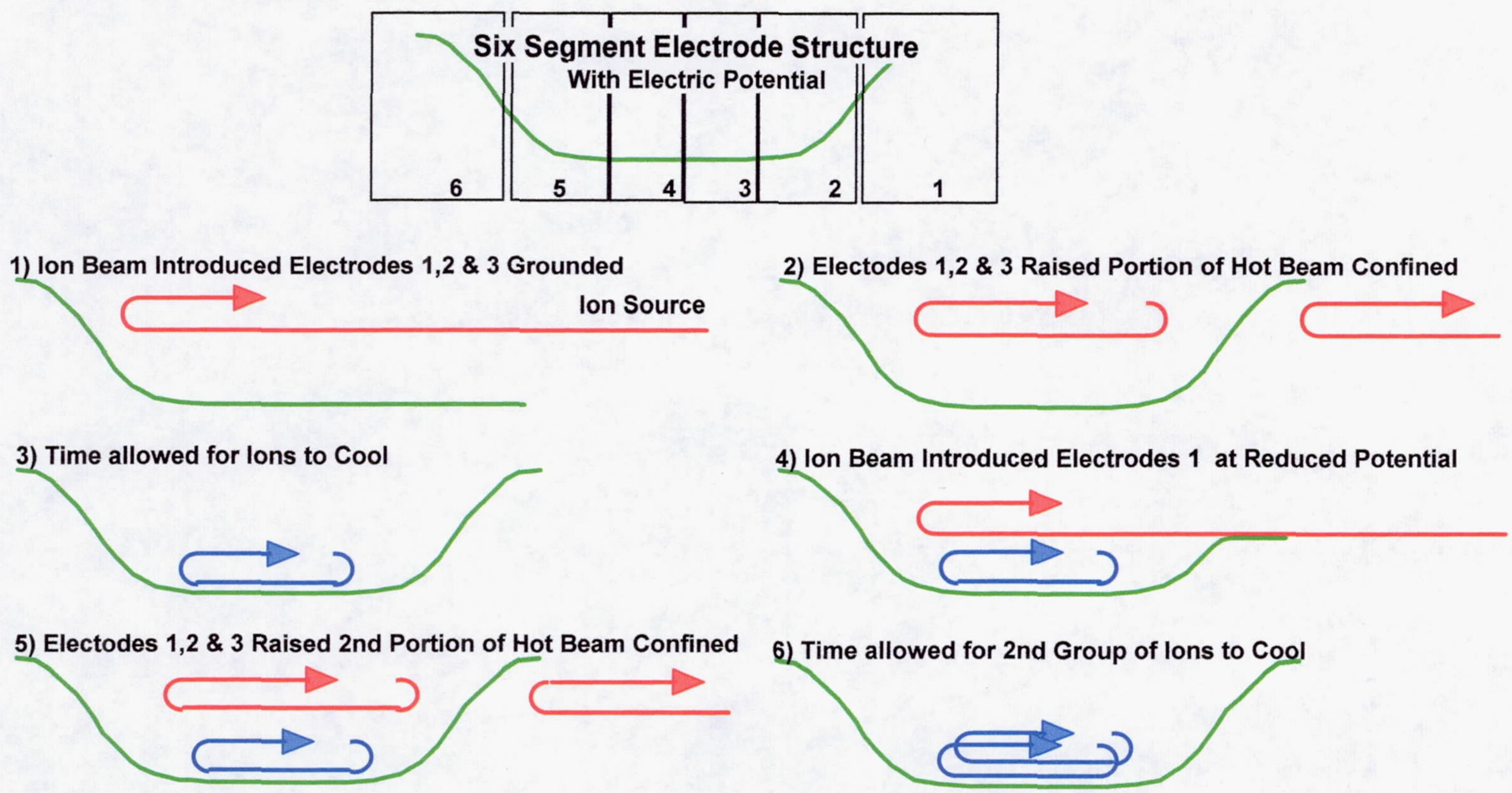




Ideal Ion Stacking Sequence

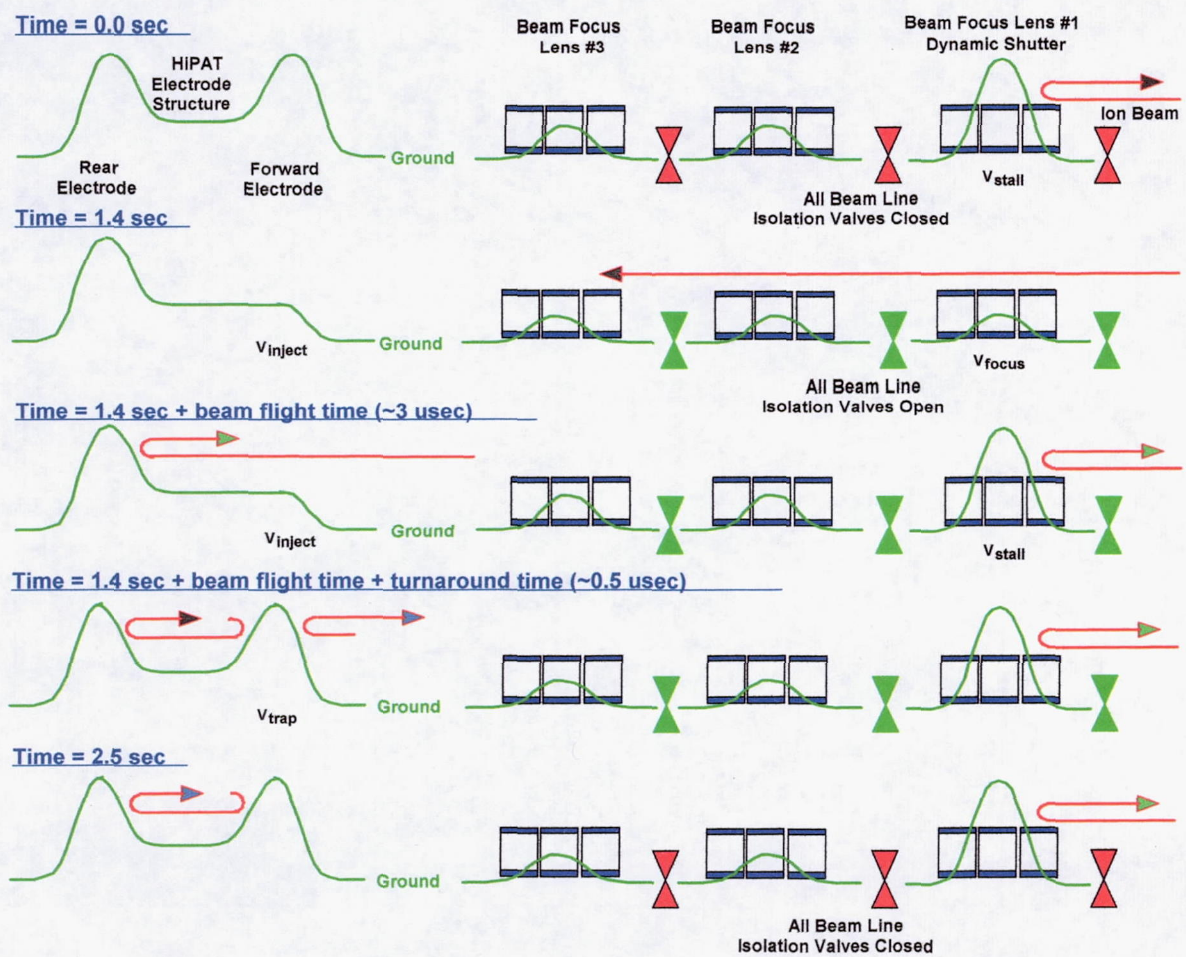
Only a limited number of ions can be captured from a single beam spill.
Reaching higher fill levels necessitates stacking, which entails the following:

- 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



Setup For Dynamic Capture

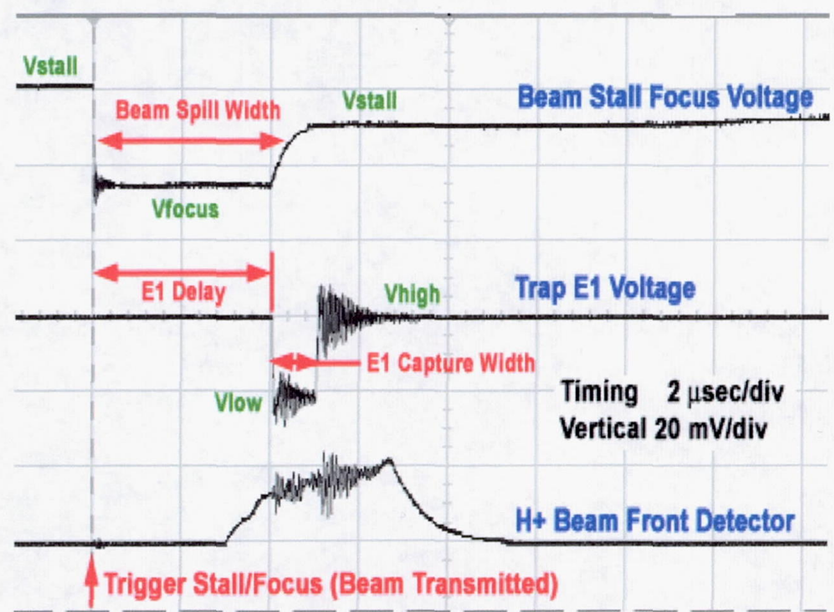
The HiPAT hardware uses the following dynamic system incorporating a series of valves, electrostatic lenses, and "trap door" electrodes.



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.

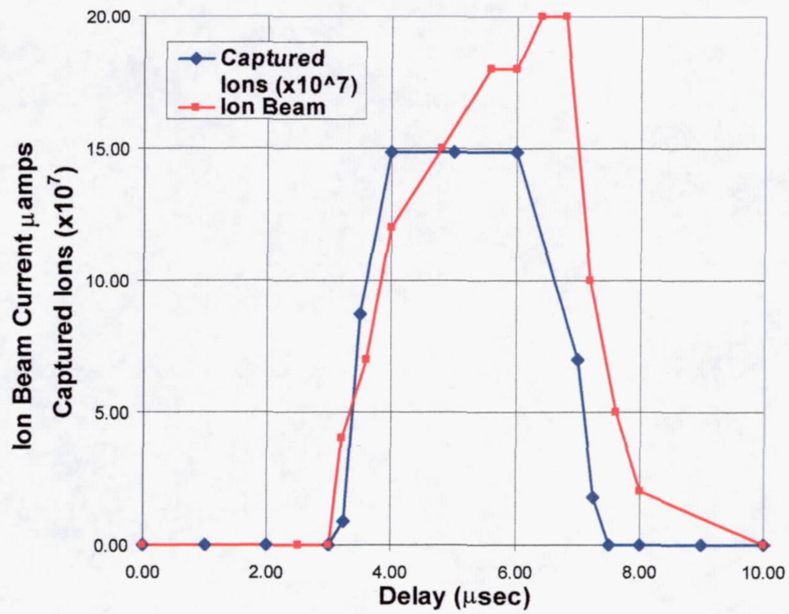
- Beam line valves used to minimize gas loading… 10^{-6} torr to 10^{-11} torr (cycle time ~2.5 seconds)
- Focusing Einzel lens used as an electrostatic shutter. Triggering between Stall/Focus (cycle time as fast as 0.1 nanoseconds)
- Trap's forward electrode (E1) voltage collapses using dump timing 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.



Dynamic Capture

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 ~1.5×10^8 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 μsec, trap electrode cycle width of 1 μsec.
- Trap flat potential well 1kV (plasma column geometry) with end potentials at 3 kV.
- Ion beam set to ~2 kV energy with an intensity of ~20 μamps.

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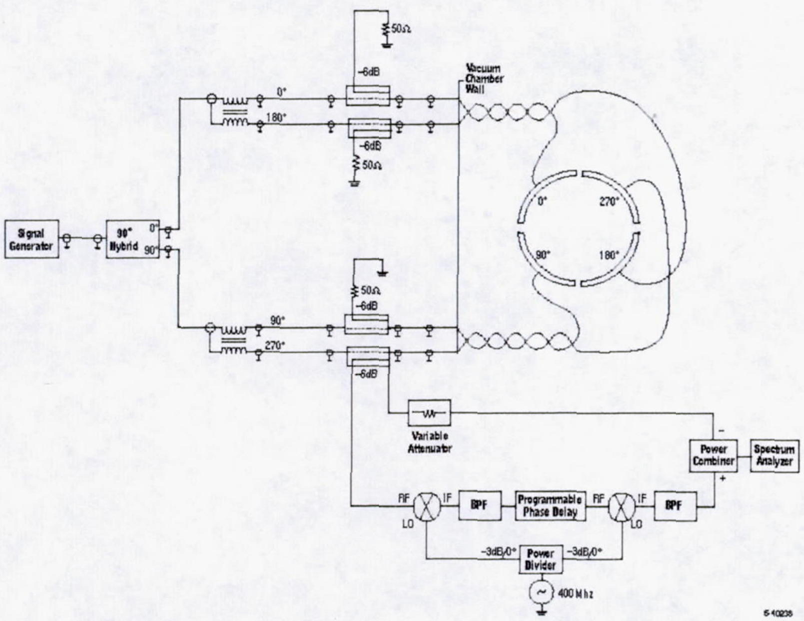
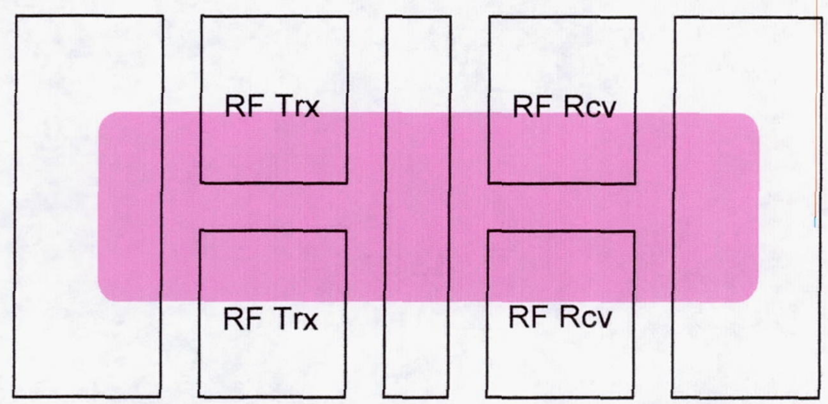
Radio Frequency Particle Detection

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.





Radio Frequency Antenna Modeling

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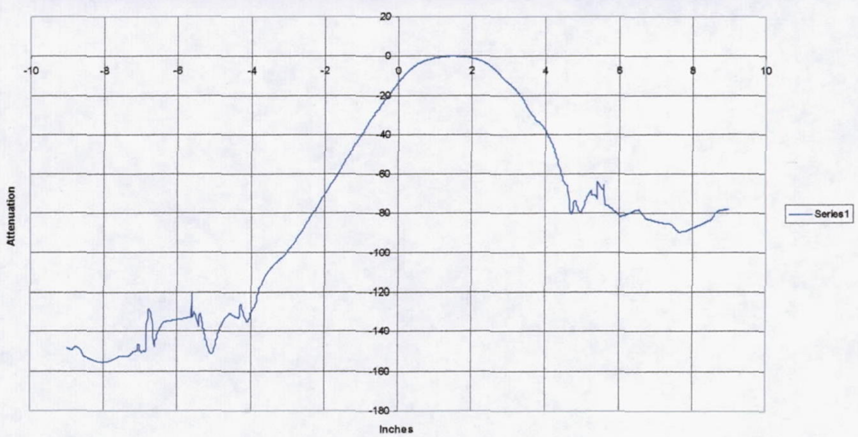
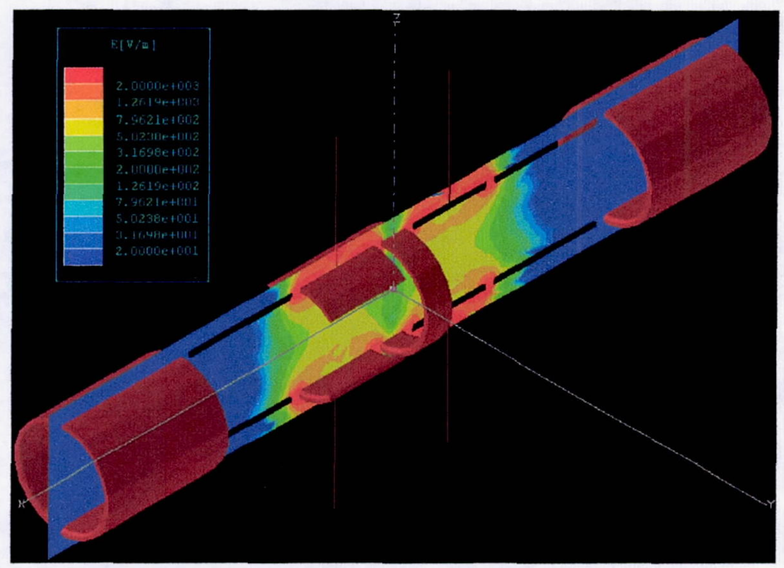
HiPAT electrode structure modeled

- 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.

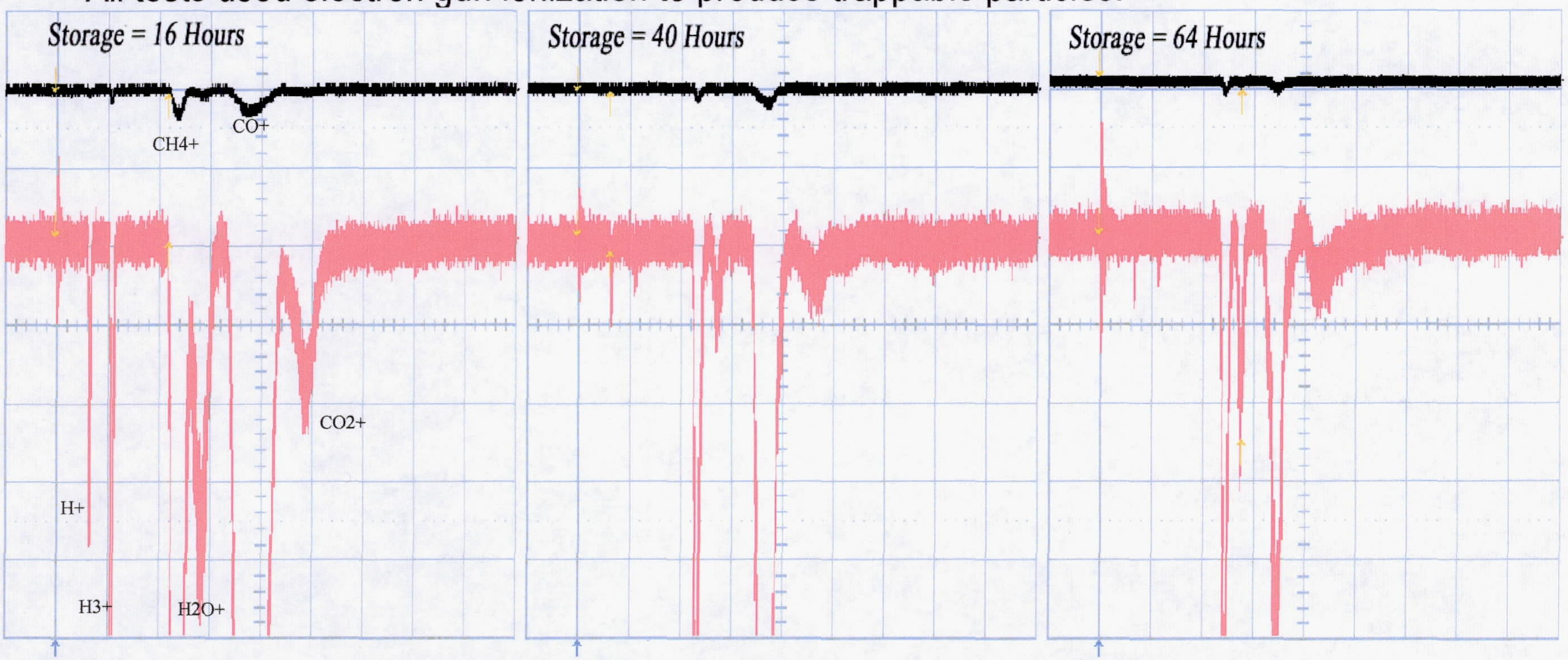




R.F. Stabilization- Low Frequencies

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.

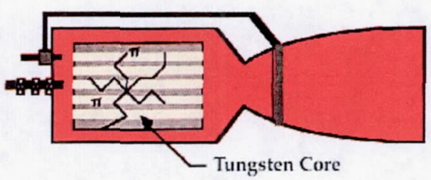
BACKUP STUFF

Propulsion Applications of Antimatter

Traditional Applications

Conventional antimatter driven propulsion concepts

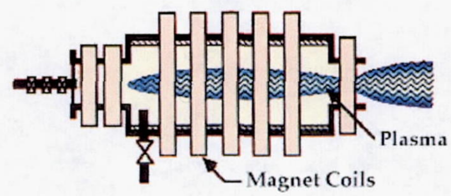
- These systems derive all their thrust from matter/antimatter annihilation
- Large amounts of antimatter would be required for operation (grams to metric tons)
  - I_{sp} = Specific Impulse (propellant usage efficiency thrust/propellant weight flow rate)
  - η_p = Efficiency of utilization (% of available 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



Solid Core

Isp - 1,000 sec

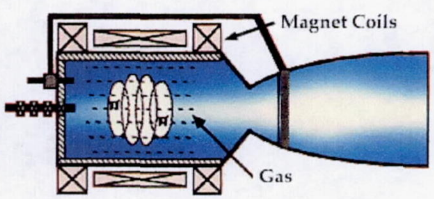
η_p - 85%



Plasma Core

Isp - 10^5 sec

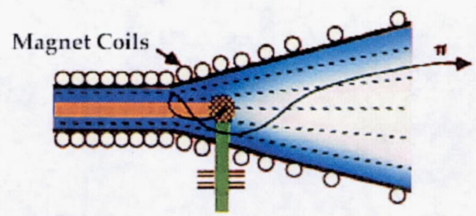
η_p - 10%



Gas Core

Isp - 2,000 sec

η_p - 35%



Beam Core

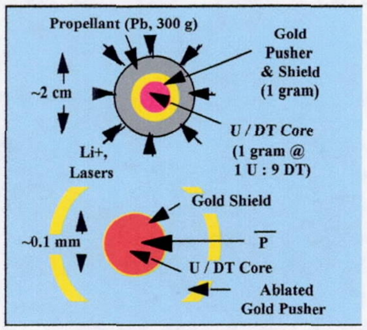
Isp - 10^7 sec

η_p - 60%

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.

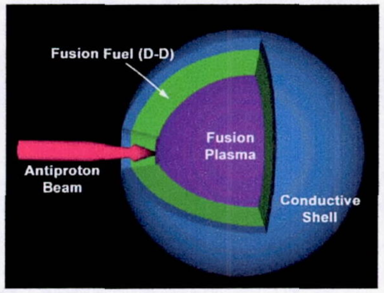


Antimatter-Catalyzed Micro-Fusion (ACMF)

Isp - 13,500 sec (Specific Impulse)
η_p - 15% (Propulsive energy utilization)
λ - 0.7 (Vehicle structure/propellant mass ratio)
β - 1.6 x 10^7 (Fusion/annihilation energy ratio)

Antimatter-Magnetically Insulated Confined Fusion (AMICF)

Isp - 200,000 sec (Specific Impulse)
η_p - 10% (Propulsive energy utilization)
λ - 2.3 (Vehicle structure/propellant mass ratio)
β - 5.0 x 10^3 (Fusion/annihilation energy ratio)



Antimatter-Initiated Micro-fusion (AIM)

Isp - 67,000 sec η_p - 84% λ - 0.2 β - 10^5	D-He3	*Isp* - 61,000 sec η_p - 69% λ - 0.3 β - 2.2 x 10^4	D-T

PROPULSION APPLICATION (Cont.)

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Comparative performance of antimatter based propulsion concepts