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Experimental determination of the stable boundary for a cylindrical ion trap

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Introduction

The first radio frequency (rf) quadrupole ion traps were designed with hyperbolic trapping electrodes and had the advantage of a working theoretical model with an analytical solution for the equation of motion for an ion. This came at the cost of a difficult fabrication process by the nature of the hyperbolic design. Cylindrical designs were found to be an easily constructed and functional alternative for ion trapping, but a sound theoretical model for this geometry has yet to emerge. While the hyperbolic theory yields approximate parameters for stable ion trapping, experiments conducted near the stable/unstable boundary require an experimental determination of this boundary.

Objective

Experimentally determine a strategic section of the stable boundary for a cylindrical RF quadrupole ion trap and compare findings to theoretical and simulated results.

Methods

Two experiments were conducted with the same basic process to determine the boundary. For each scan line V_0 is held constant while U_0 is increased by a small amount (0.2 Volts) for each data point until we no longer see a signal intensity for our target ion, nitrogen singly charged (N^+).

Experiment 1

- Trapping parameter values being investigated are held constant near the boundary
- Experimental boundary determined for ion "storage" times 345 ms and 690 ms

Experiment 2 (Delta U0)

- Ions created and cooled within ideal trapping parameters for 700 ms
- Parameters are then abruptly changed to values under investigation
- Ions ejected after 2 ms exposure to near boundary parameters

Simulation and Theory

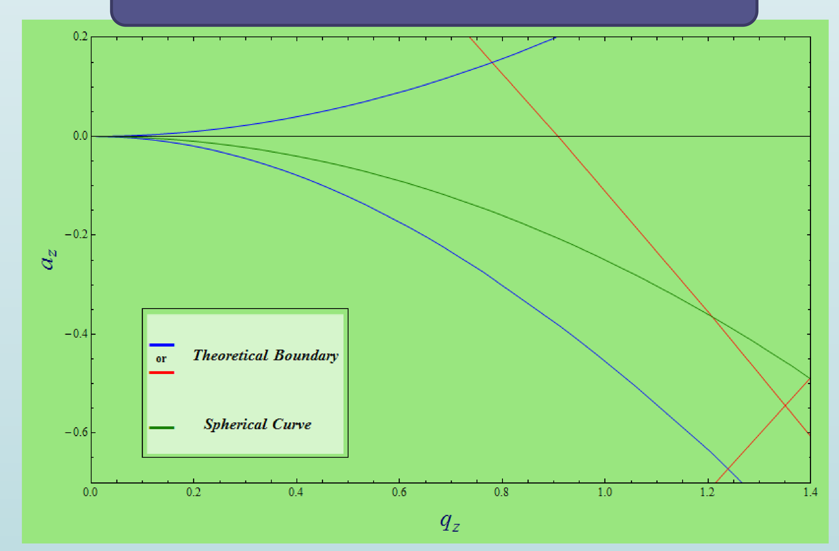
For cylindrical and hyperbolic traps the two end cap electrodes are held at ground during the trapping sequence while the ring electrode carries an AC potential (V_0) with a DC offset (U_0). The SimIon program allow us to numerically determine if an ion is trapped by calculating forces on an ion and it's motion in time-steps. This becomes a valuable tool in the absence of a theoretical model for cylindrical geometry.

For hyperbolic geometry, these boundary conditions result in the ion's equation of motion to be in the form of the Mathieu differential equation

$$\frac{d^2u}{dv^2} + (a_u - 2q_u\cos(2v))u = 0$$

Where q_u and a_u are defined to be linearly related to V_0 and U_0, respectively. The solutions to these equations are known to have well q_u defined regions defined by and a_u that result in bounded stable motion.

Mathieu Stability Diagram



The theoretical stability diagram for hyperbolic ion traps based on the Mathieu differential equation

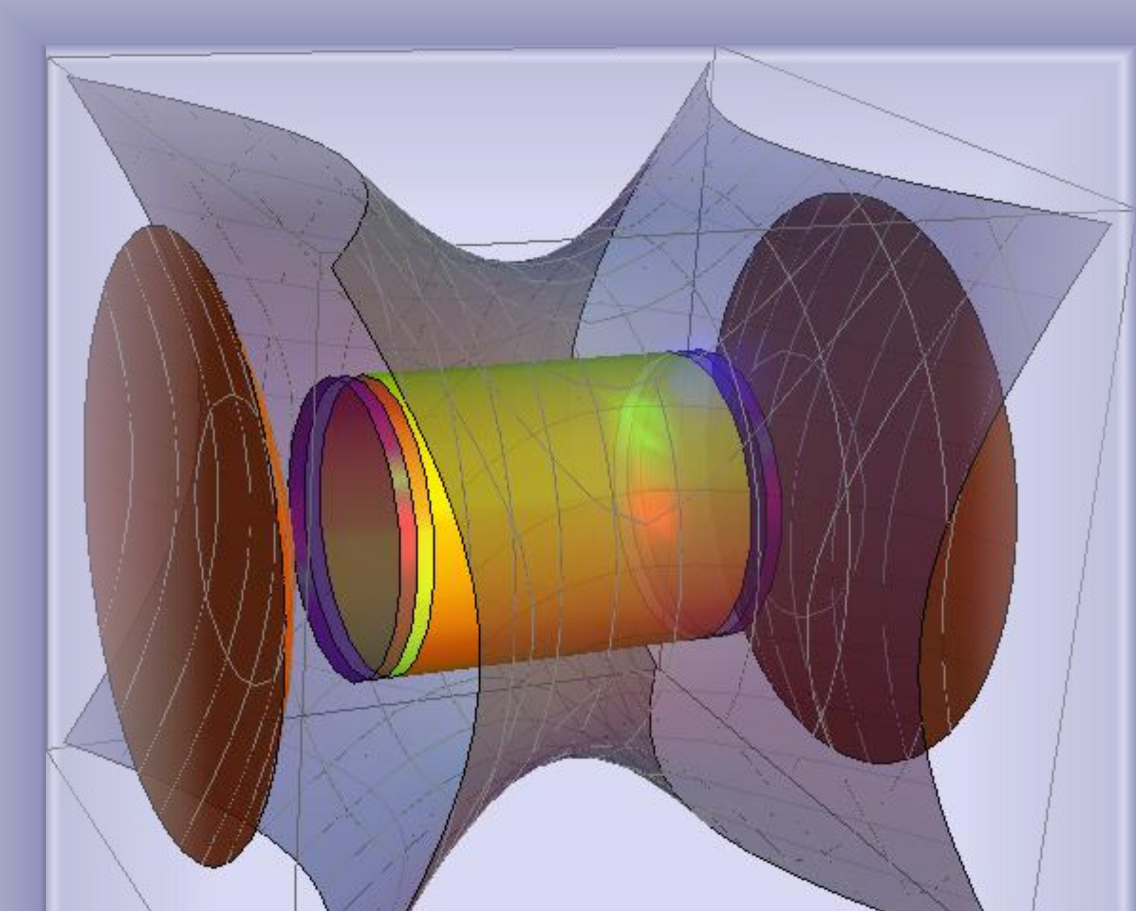
The boundary conditions in the cylindrical case do not yield a simple analytical solution, however the potential surfaces near the center of the trap approximates those produced by the hyperbolic electrode geometry. We then assume similar bounded trapping conditions for cylindrical geometry and compare results to the hyperbolic case using the same definitions of q_u and a_u.

System Components

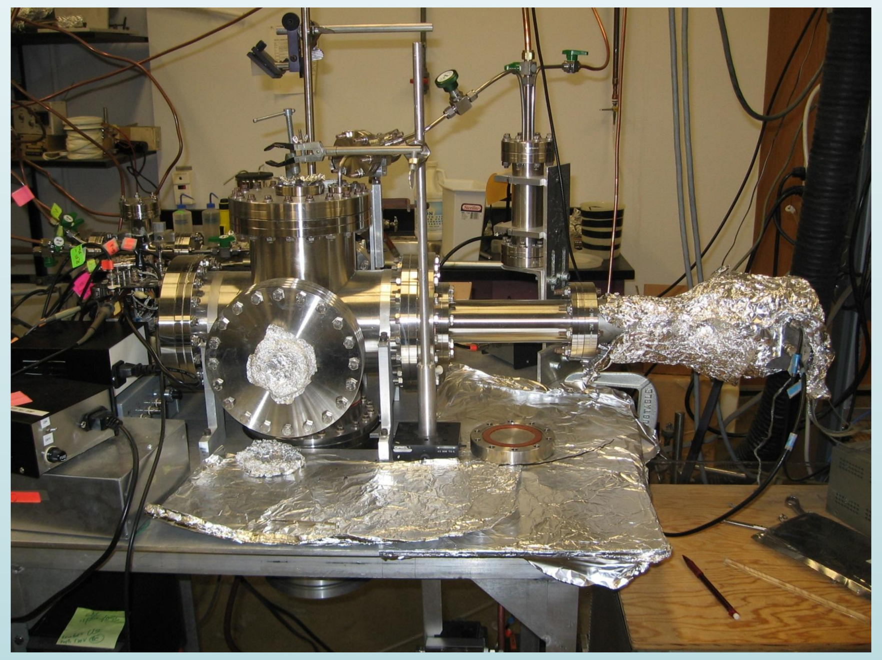
Close-up of the trapping chamber (top) the gas resoviers (right) and the timing electronics that must communicate with the trap (left)

Ion Creation

The trap resides within a high vacuum environment with a background pressure of 5×10^{-11} Torr. A gas delivery system supplies this environment with a stable amount of nitrogen (N_2) as the experiment progresses. N^+ ($^m/_q = 14$) is produced by electron impact ionization of N_2. Electron impact on N_2 also produces a ($^m/_q = 28$) significant quantity of N_2^+. However, the ion trap is optimized to one ion of ($^m/_q = 14$) and N_2^+ ions are expelled from the trap.

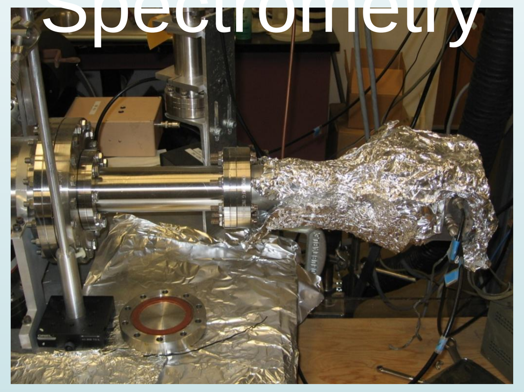


RF Quadrupole Ion Trap



Picture of experimental apparatus used for this project. The Electron Gun is on the left side of the trap while the TOF is on the right side leading to the MCP

Mass Spectrometry



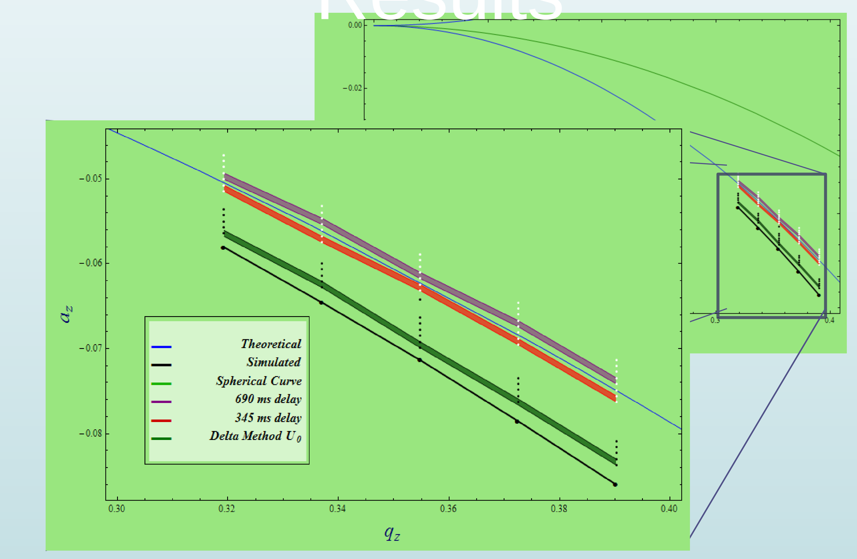
Close-up of the Time of Flight (TOF) tube and Multichannel plate (MCP)

After the designated trapping period, ions are extracted from the trap, mass analyzed by a TOF mass spectrometer before being collected by a detector.

Ion Detection

A strong potential difference is placed on the end-cap electrodes, forcing the ions out of the trap and providing them with a relatively common kinetic energy. As a result, the ions travel along the Time of Flight (TOF) tube at a distinct speed dependent on its mass-to-charge ratio. Then they arrive at a multichannel plate (MCP), placed a set distance from the trap center, at a distinct time. The ions are then sampled as they impact the MCP generating a signal. When viewed as a function of time, we can identify the ion by its characteristic arrival time.

Global Comparison of Results



The outcome of our two experiments are displayed here and compared to simulated and theoretical results

Results

- First experiment resulted in a disagreement for the determined boundary for separate ion storage times
- Noticed a difference of 0.5 Volts between boundary estimates
- The Delta U_0 approach agrees well with simulated boundary
- Experimental boundary on average within .6 Volts of simulated boundary

Conclusion

- Creation or storage of ions near the stable boundary adversely affect resolution and ion population
- Trap design appear to "leak" ions near boundary over time rather than conforms to stable/unstable characteristic as in theory
- Delta U_0 approach minimizes these complications with small exposure time

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