Lab 4: Paul Trap for Charged Particles

November 2, 2021

1 Introduction

1.1 Background Reading

1. Wolfgang Paul, "Electromagnetic Traps for Charged and Neutral Particles", Nobel Lecture, (1989).

2. H. Winter and H. W. Ortijohann, "Simple Demonstration of Storing Macroscopic Particles in a 'Paul Trap' ", Am. J. Phys. 59, No. 9, (1991).

1.2 Motivation

Traps for individual charged particles, such as Penning traps and Paul traps, have a history of being used for some of the most precise measurements in physics, including measurements of the electron g-factor, atomic clocks, and quantum computing. In this experiment, you will trap macroscopic charged particles in a Paul trap.

This experiment will demonstrate the operating principle of the Paul trap as well as the complex motion which results from the combination of the micromotion, driven by the oscillating trapping field, and the secular motion, which is the motion of the particle in the trapping pseudopotential created by the oscillating field.

1.3 Techniques

In this lab, data will be acquired by analyzing images of the particle taken with a high-speed camera. You will use a pre-written program to acquire images from a Basler acA1920-40um high-speed camera with a low-magnification camera lens. The particles are trapped by high voltage applied to a ring electrode (through a 50:1 step-up transformer) oscillating at 60 Hz. The images can be analyzed by cross-correlation, with trackpy, or by an algorithm of your own to track the center of the particle from frame to frame.

2 Objectives

These objectives are intended to guide your experiments. They are not a step-by-step procedure.

1. Calibration:
   Measure the camera and lens calibration in both horizontal and vertical directions by taking images of the calibration target (or ruler) in two orientations. You should use this calibration for all remaining parts of this lab (convert all data from pixels to meters or μm). Compare your results to the expected calibration based on the specified pixel size of the camera and magnification of the lens.

2. Combined motion:
   (a) Load a single particle into the trap (or at least only have one in the field of view, with no others nearby). Record (for a long time) and plot the thermally-driven motion of the particle at atmospheric pressure in the time and Fourier domains. Use a high enough frame rate to record both the micromotion and secular motion ($\geqslant$ 150 Hz suggested). Identify the micromotion of the particle due to the oscillating field and the secular motion of the particle in the psuedopotential in the Fourier spectrum.
   (b) Make histograms of the displacement of the particle due to thermal motion for both the vertical and horizontal motion at atmospheric pressure (you need a long run to get a low-noise distribution here). Remove the micromotion in the Fourier domain, leaving only the secular motion, and plot the new histograms.
   (c) Record the transient response of the particle after "tapping" the table or "kicking" the particle by another means. Analyze the motion in the Fourier domain.
3. Stability:
   Measure the range of voltages over which you can keep particles trapped. Does this range depend on how many particles are trapped? Why?
4. Separating the motion in real time: Observe the motion of the particle with a 60 Hz frame rate and a short exposure time to effectively "freeze" the micromotion. Explain the behavior of the particles and observe their response to a perturbation (e.g. tapping the table). Adjust the frame rate to a few Hz away from 60 Hz to help visualize the micromotion. Describe and explain what you observe.
5. Multiple particles:
   Load multiple particles into the trap and record images of the particle arrangements that form. Explain the patterns you observe and why these are sometimes called Coulomb crystals.

3 Questions

These questions should be specifically answered in your lab notebook, and can also serve as a guide for discussion in your lab report analysis.

1. How does the physics of a particle in a Paul trap compare to that of an optically trapped particle in the previous lab? Is the motion over or under damped? Are they more similar with the micromotion removed?
2. Calculate the apparent particle mass by making a histogram of the velocity (or is velocity squared better?) and fitting a room-temperature thermal distribution to it with mass as a fit parameter. Should this velocity include the micromotion? Justify your approach and complete the calculation. Is the result reasonable?
3. OPTIONAL (undergraduate students), REQUIRED (graduate students):
   Compare the calculated stability range of the trap with what you observe. Estimate any unknowns. Do your experiments agree with the calculation?

4 Hints

1. There is high voltage on the ring (up to ~ 6 kV)! Do not touch it!

2. Loading particles: charge up the wand, dip it in the particles, and tap it on the edge of the trap ring. If you end up with too many particle trapped, lower the trap voltage until some fall out.

3. The trap can be very sensitive to air currents. Even walking by can knock out trapped particles.

4. The magnification of the lens is dependent on both the zoom and focus adjustments. You need to recalibrate the magnification any time you change the settings.

5. Make the camera exposure time short to avoid saturating the camera and blurring out the particle image.

6. You can "remove the micromotion in the Fourier domain" by taking the Fourier transform of the motion (horizontal or vertical) and replacing the values at the unwanted frequencies with zero. Then, inverse FFT to get back to the time domain. Don't square or take the absolute value of the FFT data – that would throw away critical data. This is really just a form of filtering.