# Trapping Lycopodium Spores in a Vertical Linear Paul Trap

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**Abstract**

Ion traps are great. Their applications in scientific research are very broad, and they can serve as an impressive demonstrational tool for open days, lectures and student labs, when adapted. Here, a linear Paul trap is oriented vertically to trap Lycopodium Clavatum spores and examine the electric fields needed to balance the pull of gravity. The spores were ionized with a statically charged PVC rod. Their behaviour inside the trap was examined to find a charge to mass ratio between 0.01 and 0.05 C/kg. Analysis of two-ion Coulomb crystals provided an estimated charge around $10^6$ $q_e$. Some recommendations are given for future spore trapping setups.

# 1 Background

Physicist and philosopher G.C. Lichtenberg once wrote, more than two hundred years ago: “I think it is a sad situation in all our chemistry that we are unable to suspend the constituents of matter free.” [1]. Similarly, in 1952, E. Schrödinger: “. . . we are not experimenting with single particles, any more than we can raise Ichthyosauria in the zoo.”[2], expressing the absurdity of confining singular particles in an experiment. Rather, he argued, we are always dealing with a quantum system, in which the single particle view breaks down, fundamentally.

And, although the process is not always simple, there now exist devices able to trap singular particles, atoms or molecules to be studied individually. These devices, known as ion traps, are used in a wide range of research. They allow for precise measurements of molecular properties [3]. Slightly modified devices can be used as mass spectrometers or ion guides and are used, for example, in protein sequence determination [4]. Applications in quantum computing are underway [5].

In order to trap an ion in free space, without it touching any part of the setup, static electric fields cannot suffice. In the most basic geometry, a static field that confines an ion’s movement in all directions needs some nonzero divergence. However, Gauss’ law states that there need always be some charge distribution present in order to cause this divergence. Hence, to confine an ion in a static field, it would need to sit on some opposite charge, and thus not be free in space. More generally, however, Earnshaw’s theorem states that ions cannot be confined to a static position in free space by unchanging electric or magnetic fields of any shape. There will always be at least one direction in which the particle is not confined.

It is important to note that Earnshaw’s theorem holds only for static singular fields. One could still trap ions by using oscillating fields or moving magnets [6]. Penning traps use a combination of static magnetic and electric fields to trap ions. Electrodes at the top and bottom of a Penning trap confine the ions axially, but drive them away radially. As they orbit around the center axis of the trap though, a magnetic force pushes the particles back towards the center of the trap [7].

## 1.1 Paul Traps

In contrast, Paul traps or RadioFrequency (RF) traps use oscillating electric fields instead. The usual configuration uses a quadrupolar field, as shown in Figure 1. This field is generated by applying opposing potentials to two sets of electrodes. In this figure, a positive voltage is applied to electrodes $A$ and $D$, while a negative voltage is given to $B$ and $C$. Having those potentials oscillate causes ions caught between the electrodes to move back and forth along one of the field lines. From there, some cooling mechanism can slow the ions down, and they will end up close to the point where the average strength of the fields is the weakest; near the center of the trapping region. This cooling can be done with laser cooling or through collisions with a buffer gas, for example [8].

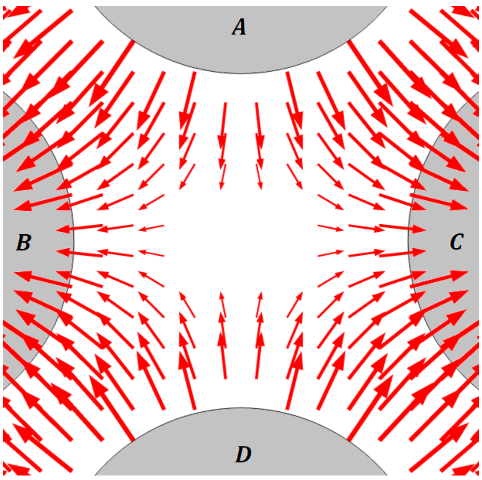


Figure 1: A quadrupole field, simulated in COMSOL.

This quadrupolar field configuration takes care of trapping in two dimensions. This shall be called radial trapping from hereon. To confine ions in the third (axial) dimension, one could revolve the electrode setup, ending up with a ring and two (hemi)spheres.

Alternatively, one could elongate these electrodes in the axial direction and introduce two electrostatic endcap electrodes near the ends, but on the center axis. The voltage applied to these should be the same polarity as the charge of the trapped ions. An example will be shown later, in Figure 5b

## 1.2 Stability

The exact constraints on the trap geometry and voltages involved can be determined by studying the relevant Mathieu equations for a linear Paul trap [9]:

$$\ddot{x} + (a - 2q\cos\omega t)x = 0 \qquad \ddot{y} + (a + 2q\cos\omega t)y = 0$$

$$a = \frac{4QV_{eff}}{m\omega^2 r_0^2} \qquad q = \frac{2QV_{AC}}{m\omega^2 r_0^2}$$

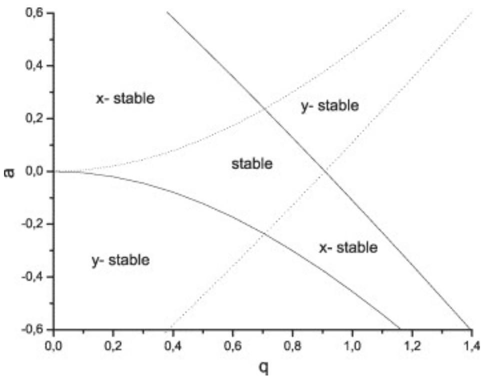



Figure 2: Stability Diagram for a Linear Paul Trap [10].

Where x and y are the radial coordinates, with the RF electrodes sitting on the axes, with a minimum distance $r_0$ from the edge of any electrode to the central trap axis. The RF potential is given by its amplitude $V_{AC}$ and angular frequency $\omega$. $V_{eff}$ is an effective defocussing potential, dependant on the voltage applied to the DC endcap electrodes, as well as the geometry and proportions of the trap. $Q$ and $m$ are the charge and mass of the trapped ion, respectively.
The stability of any Paul trap depends on the parameters $a$ and $q$, in addition to the presence of some cooling mechanism. If the trap is operated in a vacuum, the ions will be confined if $a$ and $q$ lie within the region labeled 'stable' in Figure 2. For trapping axially, $V_{DC}$ must have the same sign as the charge of the ions. Hence, $a$ must be positive.

# 2 Trap Design

For the construction of an ion trap, it is important to know what ions will need to be trapped. Here, we take microscopic particles, so that they may be made visible with laser light.

In particular, the particles studied here are spores from the lycopodium clavatum club moss. These spores are uniform in shape and size, as shown Figure 3. The diameter of these particles lies between 25 and 35 microns, and their mass is around 4 to 5 nanograms [11],[12].
If we assume a typical charge of $10^5$ $q_e$ [12], we find a charge to mass ratio of 0.003 $C/kg$ or, with a maximum charge of $3 \cdot 10^5$ $q_e$, a maximum $q/m$ of 0.01 $C/kg$, or $1 \cdot 10^{-10}$ $q_e/m_H$. For a linear trap where two opposing electrodes are spaced 15 $mm$ apart, this means that the RF electrodes should be connected to a signal of a couple hundred Volts in amplitude, at a frequency of 50 or 60 Hertz. This is roughly the AC signal that wall sockets provide in most parts of the world. Specifically, in mainland europe, mains power is provided at an RMS amplitude of 230 $V$ at 50 $Hz$. This means a very simple transformer should be able to supply the RF signal needed.

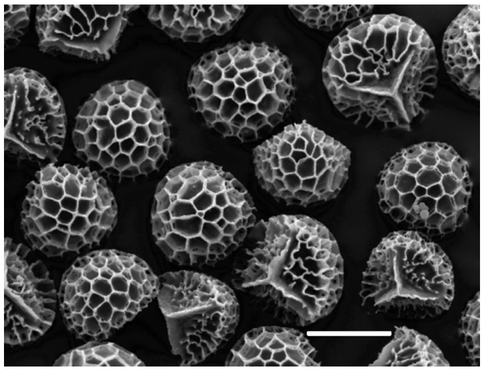


Figure 3: Scanning Electron Microscope image of Lycopodium spores. The scale bar is 25 $\mu m$ [11].

If the trap is oriented vertically, gravity would prevent the trapped spores from leaving the trap at the top. The pull of gravity would be around forty to fifty picoNewtons, meaning an electric field of a couple thousand $V/m$ would be needed to prevent the ions from falling down. If the electrode used for this is relatively small compared to the rest of the trap, the field will spread out in a wide manner. Then the upwards force provided will decay rapidly along the longitudinal axis, roughly according to an inverse-square law, as shown in Figure 6b. Hence, the potential applied to it must be around the hundred volt region, at least.

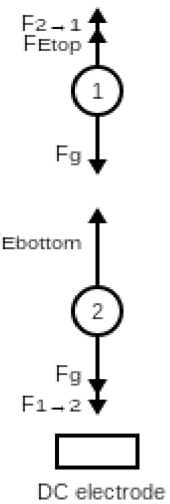



Figure 4: A diagram of two ions in a vertical Coulomb crystal. Radial trapping forces are not shown.

With this setup, it cannot be known precisely what the stability parameter $a$ will be, as the voltage required to balance out gravity might not simply be the voltage used to calculate the parameter $a$. However, it can be difficult to compute $a$ in the first place, since it also depends on the specific geometry and proportions of the trap.
It is possible to trap multiple ions at the same time. Their mutual Coulomb repulsion would balance with the trapping forces as they sometimes form a regularly spaced mesh of ions. These structures are known as Coulomb crystals [13]. In this vertical layout, the relevant vertical forces for two ions in a crystal such as the one shown in Figure 4 are:

$$|F_{1,z}| = |F_{Etop}| + |F_{2\to1}| - |F_g| \ , \qquad |F_{2,z}| = |F_{Ebottom}| - |F_{1\to2}| - |F_g| \qquad (1)$$

Where we assume the mass and charge of these ions are identical and they are both at rest. Only the absolute values of the forces are given, directions are taken care of through plus and minus signs. The gravitational force, $F_g$, affects the particles equally. $F_{i\to j}$, The mutual Coulomb repulsions on $j$ due to $i$ are also equal, but face opposite directions. Since the electric field is not the same for the top and bottom ions, neither are the electric forces due to the DC electrode $F_E$. In equilibrium, the total forces on each particle $F_{1,z}$ and $F_{2,z}$ are equal to zero.
Most of the theory thus far was built on an underlying assumption of a vacuum, but the physical device constructed for this paper was operated in air at standard pressure (1 $atm$). This is not a problem, as the collisions with air molecules just damp the motion of the trapped ions. The particle Reynolds number in air is low enough that the effect of the surrounding gas can reasonably be described by Stokes damping [14]. As the spores can not get accelerated to very high velocities, confining them within the trapping region becomes a fair bit easier. See [15] for the specifics for a cylindrically symmetric quadrupole trap.

## 2.1 Simulations

Before starting construction, it can be useful to do some simulations to check if the trap design will suffice for the intended use. For this end, the program COMSOL was used.

### 2.1.1 The Two-Dimensional Case

First, simulations of a two-dimensional slice were done. Four copper electrodes with diameters of 12 $mm$ were separated from the origin by 7 $mm$. This diameter was chosen with construction of the physical trap in mind, as some copper tubes with an outer diameter of 12 $mm$ were available for use. Some rough calculations provided the distance of 7 $mm$. A circular region around the electrodes with diameter 48 $mm$ was added for the particles to propagate in. This geometry is shown in Figure 5a.
Once the geometry was constructed and materials were assigned, the physics components Electrical Currents (ec) and Charged Particle Tracing (cpt) were added. In Electrical Currents, two terminals were added, each to a set of opposing electrodes. The first was assigned a voltage of $V_1(t) = 162.5 \sin(100\pi t)$. The second terminal was set to $V_2(t) = -162.5 \sin(100\pi t)$. These correspond to two 50 $Hz$ signals with an RMS amplitude of 115 $V$, 180° out of phase of each other.
In Charged Particle Tracing the particle properties were set to a charge of $1 \cdot 10^5$ $q_e$ and a mass of 4.7 $ng$. The program was told to have the particles interact with an electric force calculated from the electric potential, as well as a friction force. This friction force was configured to a collision cross section of $\sigma = 4.909 \cdot 10^{-24}$ with a background number density of $N_d = 2.5 \cdot 10^{25}$. The collision cross section would have been the cross section of one ion, but was scaled by a factor of $10^{-14}$. This was done because

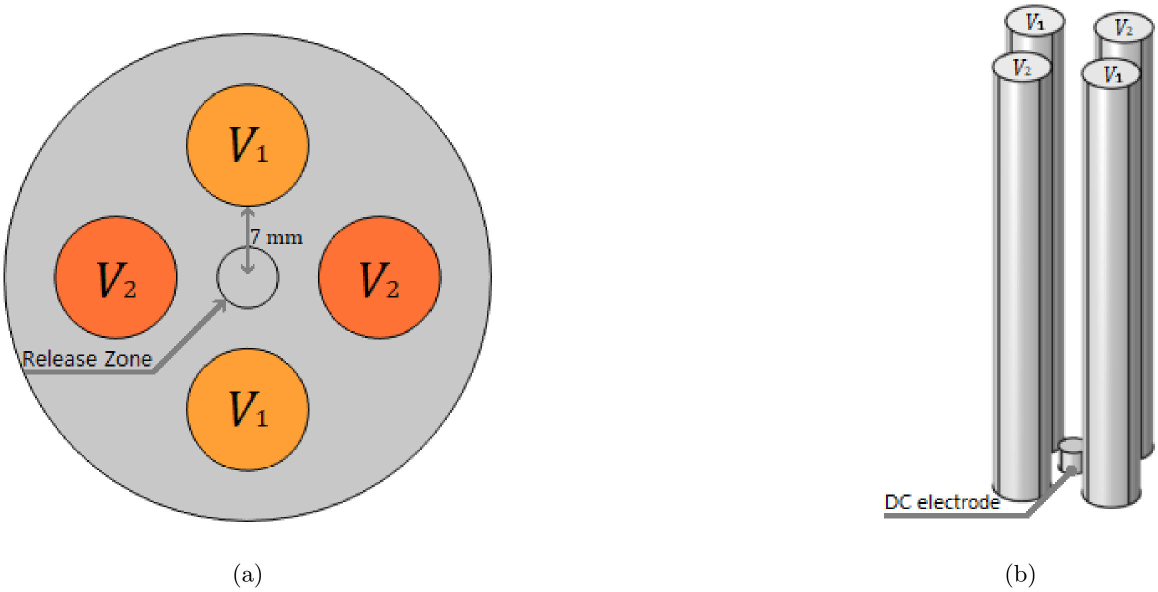



Figure 5: An overview of the geometry used in the simulations.

COMSOL had assumed the friction force to be proportional to the particle's mass, rather than the mass of the background molecules [16]. Finally, particle-particle interaction was enabled through the Coulomb force. All these forces and interactions are set to occur throughout the air domain. Particles were told to freeze in place upon collision with any boundary, whether that be the end of the air domain or the edge of any electrode. This made it fairly simple to observe whether the ions orbits were too large for the trap.

Up to 100 particles with the properties listed above were released from a circular zone in the center of the trapping region. This release zone had a diameter of 6 $mm$. The initial positions within this zone were distributed randomly, such that each particle in a simulation had a unique starting point. The initial velocities were set to 0.1 $m/s$ in random directions.

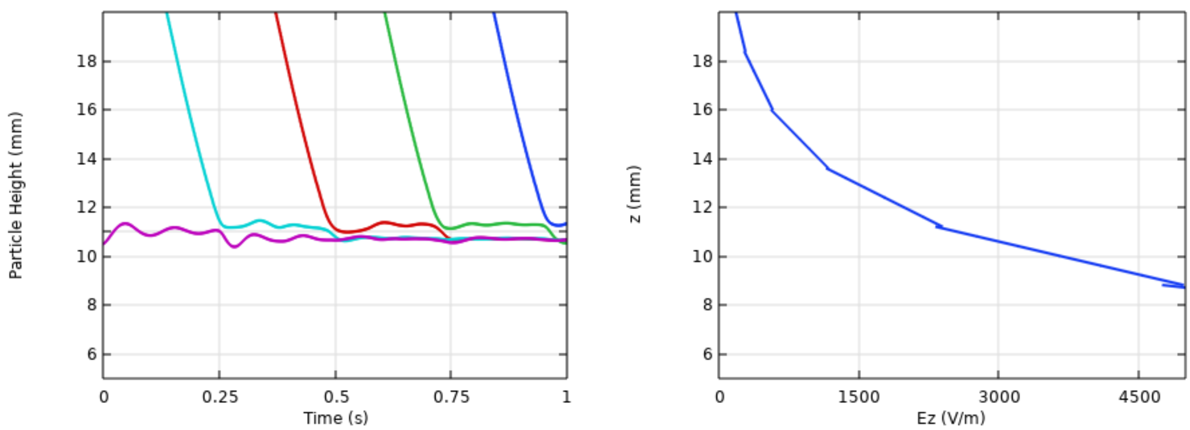
Two studies were performed. The first specifically computing the Electric Currents. The second then took those results as input for the Charged Particle Tracing. This way, the charge or mass of the ions could be changed quickly, without having to re-do the (ec) computations. However, it was usually the AC voltage or trap geometry that was changed, rather than particle properties, requiring both studies to be repeated anyway.

In both studies, a time-dependent solver was used to investigate the dynamics of the trap. These solvers recorded the situation in increments of 2.5 milliseconds, until a simulated time of one full second was reached. Generally, it could be seen whether the trap was stable or unstable after half a second or so of simulated time. Unstable ions were usually ejected after only a couple periods of the RF signal had passed. The small increments were taken out of the fear of skipping peaks, as the fields due to the RF electrodes would oscillate with a period of 20 milliseconds. However, it seems COMSOL does include what happens between these recording times in calculations to some degree. This was discovered after the simulations were all completed, by trying to record only the nodes in the RF signal. As this was a sine wave, with a frequency of 50 $Hz$, taking time increments of 10 milliseconds would only record the points at which the voltage on the electrodes was zero volts. Even then, 50 ions were confined to the trapping region for a full second, showing roughly the same behaviour as with the shorter time steps.

One could probably get away with using slightly larger time increments, especially for the (cpt) part of the simulation. Although some particles might move through an electrode between the recording times, without freezing. To prevent this from occurring as much as possible, the peak amplitudes on the RF electrodes should always be recorded. The oscillating motion of the particles in the simulation is similar to that of a harmonic oscillator, where the maximum displacement from the center coincides with the peak of the driving force.

### 2.1.2 The Three-Dimensional Case

For the three dimensional case, the geometry of the two dimensional simulation was copied. The electrodes were now constructed as cylinders, 10 $cm$ in length. A DC electrode was added to the bottom of the trapping region, with a diameter of 6 $mm$, shown in Figure 5b. Not shown is a cylindrical region of air, which was constructed around the entire trap, for particles and electric fields to propagate through. The voltages on the RF electrodes were the same as before. The DC electrode held a voltage somewhere between 100 $V$ to 2500 $V$, depending on the simulation.
In the (cpt) physics component, the same forces as before were added. A constant downward force with a magnitude of 9.81 times the particle mass was added to simulate gravity.
Again, the simulations were done in two separate studies. One solely for the electric currents and another for just the particle tracing. For this case, several spores were released at rest from the central axis, evenly spaced. With all the voltages and settings configured as described above, the simulated spores were stably confined in the trapping region for at least five seconds, as they all bunched up near some equilibrium point. They did not really seem to repel each other strongly enough to form Coulomb crystals, as multiple ions were confined into a space less then 2 $mm$ wide. Here, they would move around and switch positions so quickly that no regular structure could be discerned, even after five seconds of simulated time.
As the simulated particles had a charge to mass ratio of $3.4 \cdot 10^{-3}$ $C/kg$, we expect the electric field needed to balance gravity to be around 2.9 $kV/m$. Indeed, when looking at a combination of graphs shown in Figure 6, we find the stable height of the ions to match up with the point where the electric field is around that value. Naturally, the exact height of this point depends on the voltage applied to the bottom electrode.



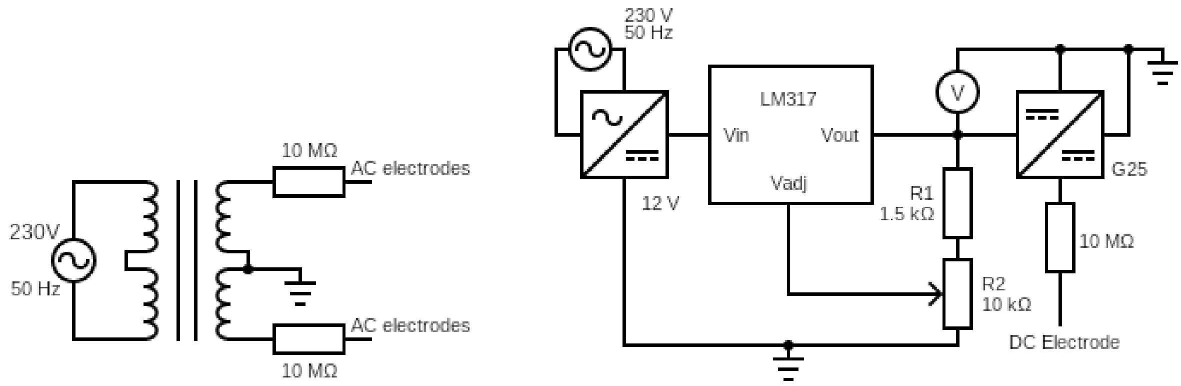

(a)

(b)

Figure 6: (a) Particle trajectories as they reach an equilibrium point in a 3D simulation. (b) The vertical component of the electric field along the center axis. The DC electrode is set to 250 $V$.

# 3 Experimental setup

For the physical device used to trap the spores, the basic dimensions used in the simulations were taken. The RF electrodes were copper tubes, with an outer diameter of 12 $mm$ and a length of 11 $cm$. The electrodes were spaced apart such that two opposing tubes had 14.5 $mm$ of space in between them. A stainless steel rod was used for the DC electrode, 6 $mm$ wide.
In order to obtain the required RF signal, a transformer was used. The transformer had four roughly identical coils and a single magnetic core, as shown in Figure 7a. It was unable to provide two opposing signals with an amplitude of 230 $V$ RMS. When the two input coils were connected in parallel to mains power, the transformer started to produce smoke in addition to an output current. Hence, the coils on the mains side were connected in series to achieve a double output of 115 $V$ RMS. The remaining two coils were both connected to ground on the center tap, and to a set of electrodes on the other.




(a) (b)

Figure 7: Diagram for the circuits used to power (a) the AC electrodes, (b) the DC electrode.

Since the current needed to drive the trap was very low, a set of 10 $M\Omega$ resistors could be inserted between the transformer and the electrodes. These resistors provided some assurance of safety while handling the trap by limiting the maximum current provided if the electrodes were ever to be touched accidentally.
In order to get the high voltage required for the DC electrode, an XP POWER EMCO G25 was used. This module is able to provide a voltage between 0 and 2500 $V$, depending on the input voltage. A negative potential was obtained by connecting the positive output terminal to ground. The circuit shown in Figure 7b was used to achieve a variable voltage on the DC electrode. Here, a voltage regulator provides the G25 with a potential of $V_O = 1.25(1+R_2/R_1)+R_2 * I_{adj}$, where $I_{adj}$ is a very small current leaking from the *adj* pin. $R_1$ was a 1.5 $k\Omega$ resistor, while $R_2$ was a potentiometer with a total resistance of 10 $k\Omega$. The resulting input voltage ranged from 1.25 $V$ to 10.2 $V$, leading to a potential on the electrode between $-250$ $V$ and $-2.13$ $kV$. A voltmeter was connected to the input voltage, showing a 3-digit value on a display mounted on the device. This display value was used to infer the DC voltage during measurements, with a conversion factor of $-208$. Again, a 10 $M\Omega$ resistor was inserted for safety reasons.
The trapping region was encased by an acrylic tube, as shown in Figure 8. This allowed visual access while preventing outside air currents from blowing away the spores. As a bonus, the tube also prevented any stray fingers from touching the high voltage electrodes, even with the $10M\Omega$ resistors in place.
To charge the spores, a PVC rod was first charged by rubbing it against some cloth or a paper towel. This should usually result in the PVC ending up with a negative charge, as it is generally found quite low on the table of triboelectric materials, right above teflon [17]. After that, the rod was brought in proximity of a pile of spores. This resulted in some separation of the charge distribution on some of the spores, causing them to jump up to the PVC rod, where they then became ionized.
The rod, now carrying ionized spores, was brought close to the trapping region, through a loading hole made in the acrylic tube, near the top of the trap. The tip of the rod was inserted horizontally until it just about passed the copper electrodes. Some spores would simply jump off themselves, but some light taps on the end still sticking out of the trap would also help to release more ions. Most of the released spores would simply pass through the trap, get ejected or fall straight down to the DC electrode. Some, however, would usually end up being caught by the trap and start floating in the air.
A low power red laser diode was mounted at the top of the trap, shining down on trapped ions. This made the spores visible to the naked eye. A camera was facing the trapping region, connected to a computer. Figure 9 shows an image taken from the software LabView, which was used to track the trapped ions and save their height to a text file once every second. This program searched for bright spots in a greyed-out image of the trap. It did so within the green rectangle, to avoid detecting reflections of light on the copper electrodes or the acrylic tube. To convert the height recorded in pixels to a height in $mm$, the height of a single trapped ion was measured by hand and by the camera for multiple different settings for the DC electrode. This way it could also be verified that the recorded and measured height share a linear relation, as shown in Figure 10.

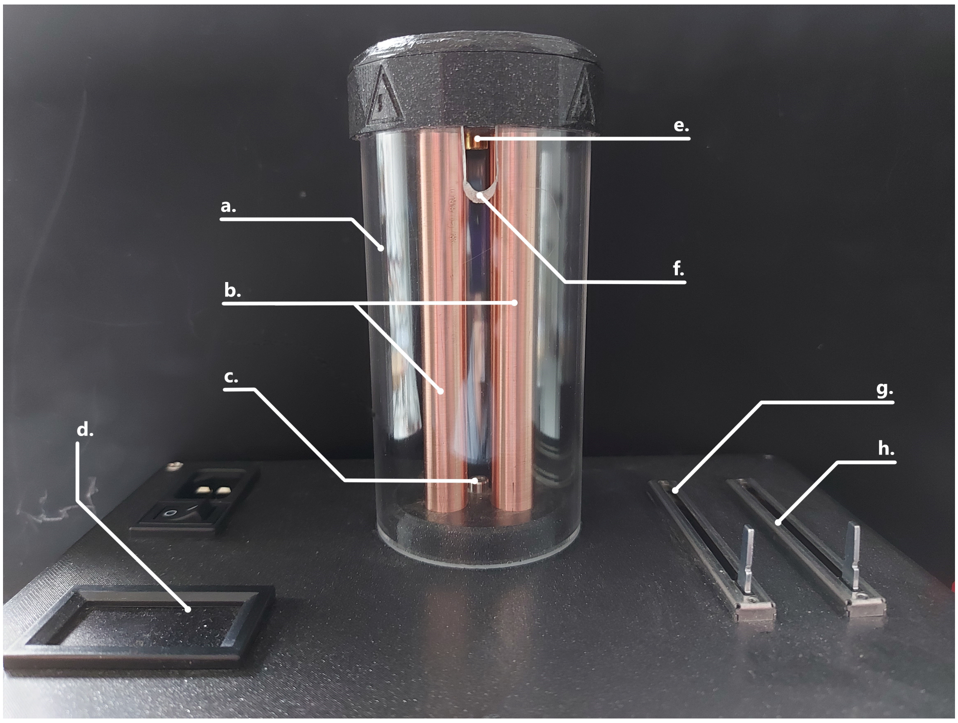



Figure 8: A picture of the trap. Relevant components are labeled. a: The acrylic tube. b: The copper RF electrodes. c: The DC electrode. d: The voltage display, which shows $-V_{DC}/208$. e: The laser diode. f: The loading hole. g: A slider for setting the laser brightness. h: A slider for changing the DC voltage. Electronics are hidden away in a grounded metal box under the grey plastic lid.

When measuring the height manually, a single ruler was not accurate enough due to a parallax error, as it could not be placed inside the trapping region, next to the ions. To counteract this, a second ruler was added to the setup, such that there was one placed behind the trap and one in front of it. Then it could be verified if the observing eye was on the same horizontal level as the trapped ion, by requiring the nearest $mm$ marks on both rulers to be equal. This way, the parallax error could be eliminated.

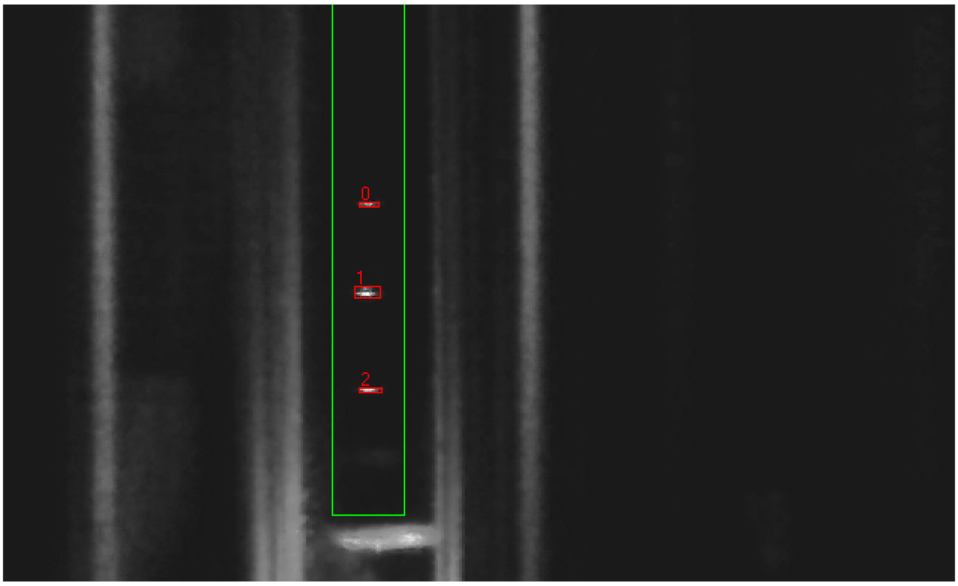



Figure 9: A Coulomb crystal made of 3 ions, tracked by LabView. The light smudge below the search area (green rectangle) is a reflection of the DC electrode on the acrylic tube.

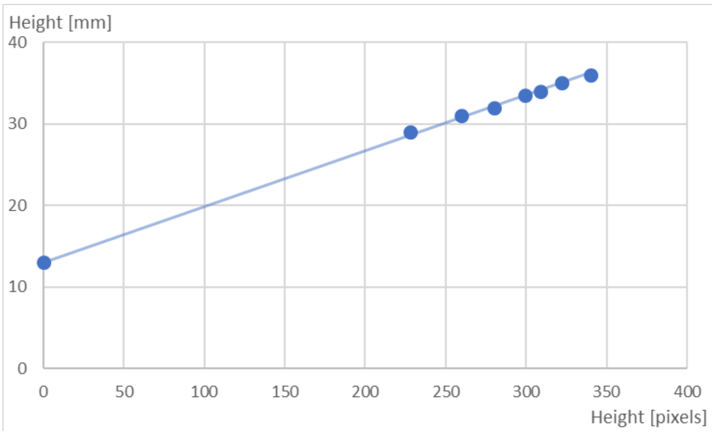



Figure 10: The height measured by hand is shown on the vertical axis, and the height measured by LabView is shown horizontally. A line was added to find the relation between the two measurement sets, with a slope of 0.07 $mm/pixel$. The 13 $mm$ offset on the vertical axis is due to the top of the DC electrode not being in line with the 0 line on the rulers. For this calibration the top of the DC electrode was at the bottom of the image in LabView.

# 4 Methods

With the setup described above, the height of a single ion was measured for different DC voltages. Then the value for the vertical component of the electric field $E_z$ at this height was found by running simulations in COMSOL, with the exact trap geometry at that specific DC voltage.
If we compare the electrostatic force on an ion due to a field $E_z$ to the gravitational force, we can find an estimate for the charge to mass ratio of trapped ions by $q/m = g/E_z$, if the two forces cancel each other.
Next, if there were two ions trapped in a vertical Coulomb crystal, the balance of forces described in equation 1 can be worked out to yield the following equation for the charge:

$$Q = 2\pi\epsilon_0 r^2 (E_{Bottom} - E_{Top}) \tag{2}$$

Here, $Q$ is the charge of the particles, $r$ is distance between them, $E_{Top}$ and $E_{Bottom}$ are $E_z$ at the higher and lower ion, respectively. Again, we assume the charge and mass of these ions to be identical. Since the electric fields are negative, and the field is stronger at the bottom than at the top, this equation will yield a negative charge for our ions.
Afterwards, either the mass or the charge to mass ratio can be found, using:

$$Q/m = \frac{2g}{E_{Top} + E_{Bottom}} \tag{3}$$

Where the $m$ is the mass of the trapped particles, and $g$ is the acceleration due to gravity.

# 5 Results

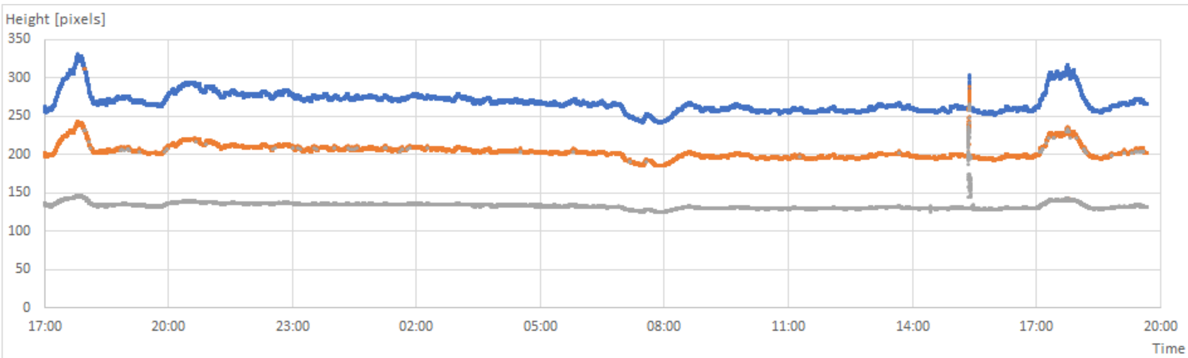
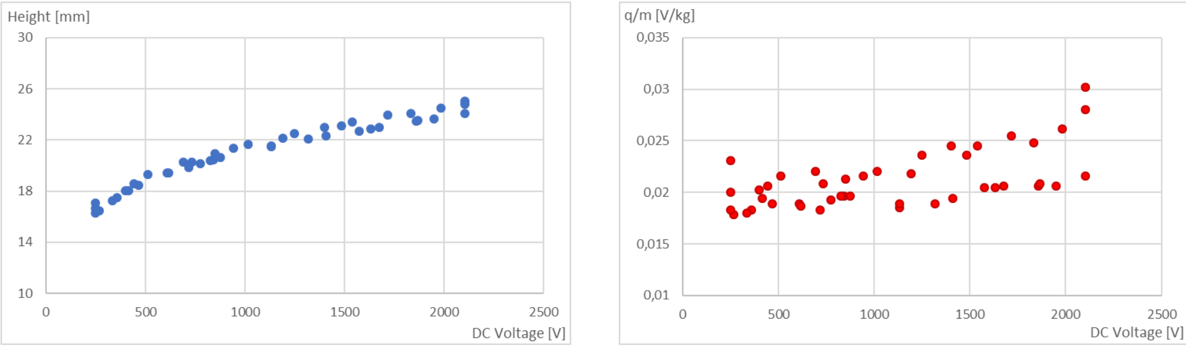



Figure 11: Three ions captured at 5 pm, observed for over 27 hours

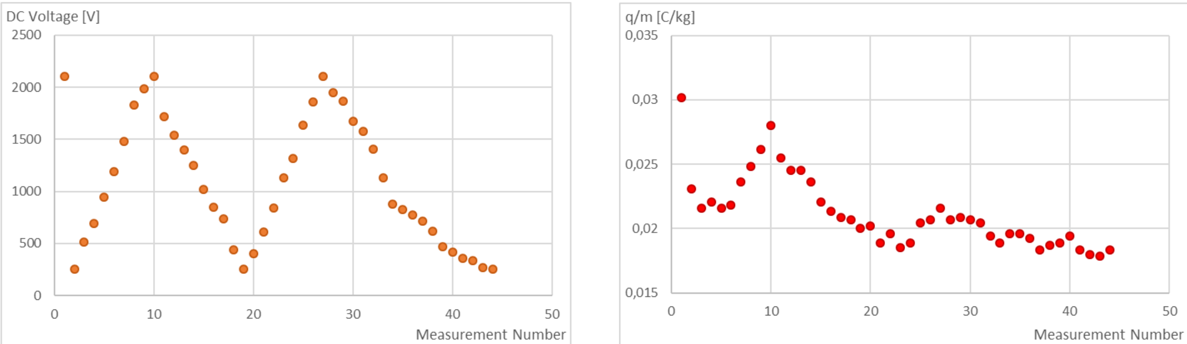
Figure 11 shows how the heights of three ions changed during 24 hours, without changing the DC voltage. Some ions were trapped more stably than others. If they were to lose charge to their surroundings gradually, a slow decline in altitude would be expected over time. Such a decline was not observable, even when an ion was trapped for over a day.
After calibrating the height measurements, multiple height measurements were done on several different ions. Figures 12a and 12b show the measured height and the resulting value for $q/m$ as the DC voltage was changed for one ion. This particular spore had been left in the trap for nearly 70 minutes beforehand. Figure 13a shows how the DC voltage was moved up and back down twice, over 44 measurements in total. If the measurements for $q/m$ are ordered chronologically, we obtain Figure 13b. This shows how the first peak in DC voltage corresponds to most of the higher measurements for this particle's charge to mass ratio.

The average value for $q/m$ found for this ion is $0.021 \pm 0.003$ $C/kg$. This is around twice as high as the expected maximum value calculated earlier. When three other individual ions' charge to mass ratio were measured, values as low as 0.01 $C/kg$ and as high as 0.05 $C/kg$ were found.




(a) (b)

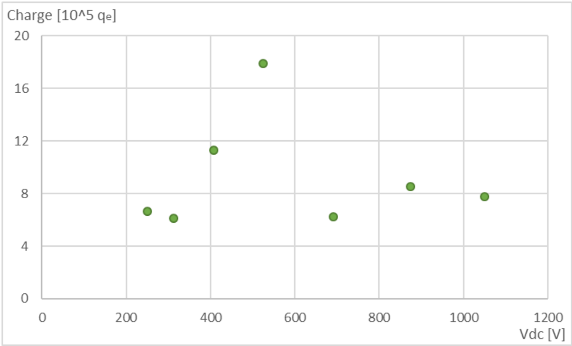
Figure 12: (a) The measured height of a spore and (b) the charge to mass ratio found, both plotted against the changing DC voltage.



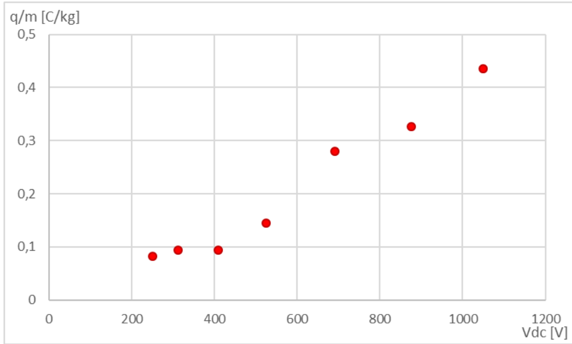

(a) (b)

Figure 13: (a) The DC voltage and (b) The value for q/m found for each measurement, ordered chronologically.

Figures 14 show some results on measurements done on a 2-ion Coulomb crystal. The heights were measured as before, as $V_{DC}$ was increased, but now with two ions in the trap. Then, Ez was determined by the use of COMSOL once again. Afterwards, equations 2 and 3 were used to compute charge and $q/m$ at different $V_{DC}$. The crystal being measured for these plots shows a charge of $9 \pm 4 \cdot 10^5\ q_e$, and a mass of $1.0 \pm 0.7\ ng$. One other crystal was measured right after this one had broken apart, and a charge and mass of $13 \pm 7 \cdot 10^5 q_e$ and $5 \pm 4\ ng$ were found. The average of the charge to mass ratios, like plotted in Figure 14b, are $0.2 \pm 0.2\ C/kg$ for the first and $0.04 \pm 0.02\ C/kg$ for the second crystal investigated.




(a)




(b)

Figure 14: (a) The charge and (b) the charge to mass ratios found for two trapped ions forming a Coulomb crystal

# 6 Discussion

The value for the charge to mass ratio found seems to be on the high side, but that could have several reasons. Perhaps the most ideal one being the fact that the trap constructed here *requires* ions of these higher $q/m$'s in order to trap them properly. Then the trap described in [12] could have been more successful in trapping spores with lower charges due to the higher voltages used on the RF electrodes. Thus resulting in lower $q/m$ values found there. In a sense, this trapping filter could mean that this trap is not suitable for finding a large distribution of $q/m$'s on ions of this size.
However, a more probable cause of inaccuracy of the results found here would be unknown factors influencing the ions. Figure 11 shows how much the trapped particles move up and down over time. At times, this drifting could happen at speeds of 1 $mm$ per minute. This could be caused by the 3D-printed PLA used for construction charging up, or stray ions floating around. For example, these stray ions could have landed near the bottom of the trap, and caused an additional upwards force on trapped ions. Something at the top of the trap also seemed to attract some ions. Quite often, multiple particles would form Coulomb crystals right under the laser. This could indicate the lens or something else getting charged positively. The components at the top that could have gathered charge were the laser lens and the 3D-printed plastic. This plastic should normally prefer to hold a negative charge, however. Glass, on the other hand, tends to gather a positive charge [17]. One last option would be the brass casing around the laser being connected to a positive voltage instead of the earth, but even if that were the case, the maximum voltage used to drive the laser is only around 4 $V$. It is hard to believe such a small potential would affect the ions so strongly.
Some more periodic drifting behaviours were also observed. Some of the ions that were trapped overnight or over several days showed some little bump around eight a.m., as shown in Figure 11. A more prominent bit of movement shows up between five and six p.m., as the ventilation and the heating in the building are turned down. This could hint at air currents driving the drift instead, as temperature differences at night and during the day may be influencing those currents. The electronics underneath the trap must generate some heat, and this heat may be more problematic when doing measurements at night, when the heating inside is turned off.
Additionally, the values found for $E_z$ might not be entirely accurate, as COMSOL simply gives some approximation of the fields. Coulomb crystals were never observed in simulations, even though they seemed quite common in the real trap. This, combined with the slightly jagged shape of the graph in Figure 6b does not yield much trust in these simulations as a highly accurate predictive tool. When ions with the mass from literature and charge to mass ratio found in measurements were simulated, they were simply ejected from the trap. Most of them get stuck on one of the electrodes, as the electric forces are too strong and oscillate too slowly to confine the ions properly.
The same issues hold for the measurements done on the two-ion Coulomb crystals, where the charge found was also a little higher than the expected value. The voltage could only be increased to 1050 $V$ or 1900 $V$, as the top ions would float away at that point. They would drift upwards due to the external influences, and would not come back down if the DC voltage was decreased again. This indicates the

possibility that, approaching this point, the external forces were becoming stronger than the electric force due to the DC electrode. The upwards trend in Figure 14b could have a similar cause, as the measured $q/m$ increases when ions are higher. If the external factors mostly cause an upwards force on the ions, and become more significant at greater heights or as time goes by, this could explain why the charge to mass ratio of the crystals seems to increase. Perhaps changing $V_{DC}$ downwards might provide some insight here. If the trend still appears, external factors might be increasing with height. If $q/m$ now increases for *lower* $V_{DC}$, they might increase over time instead.

The results found from the Coulomb crystal analysis are questionable. The uncertainties are quite high due to the wide distribution of charge measurements on each crystal. As a result, the mass also comes with a ridiculous uncertainty. Figure 14a shows how the charge seemed to change during the measurement. Obviously, the physical charge on the ions should not change as a function of the DC voltage. The fact that it is, indicates some unreliability in the measurement setup. These measurements could probably be repeated with greater precision, by requiring a more stable crystal to be trapped. Then, the measurements could be repeated on the same crystal. In order to increase accuracy, some external factors will have to be eliminated. Some graphite was applied to the plastic at the bottom of the trapping region, by rubbing a pencil along the surface. Although this was supposed to help mitigate static charges collecting on the PLA, this did not completely get rid of the distortions in the force balance of the trapped spores.

It could also be the case that the theory behind the analysis is flawed. The leap from equation 1 to equation 2 assumes that the charge of the two trapped particles is the same. In fact, it requires both charge and mass to be *identical*, even though the values found for the charge to mass ratio span from 0.01 $C/kg$ to 0.05 $C/kg$. This simplification in the theory could be another cause for the unexpected shape of the graph in Figure 14b. Actually, the theoretical expectations for single trapped particles might be flawed as well, as it is assumed that individual spores get trapped while they might clump together at times. In some cases, a trapped ion would spontaneously break into two or more pieces, indicating that it was *not* a single spore. One would expect clumps of spores to have a lower $q/m$ though, as the mass scales with the volume, while the charge collected should scale with the surface area. Then the charge to mass ratio should have an inverse relation with the general size of a particle clump holding a surface charge. Thus, it should not be likely to trap clumps with greater $q/m$ than that of single spores.

The image produced by the camera was not the clearest it could have been. Certainly, better cameras exist with higher resolutions. Apart from that, the acrylic tube distorted the image somewhat as well, making most spores show up as horizontal lines, even if they did not have any sideways motion. This distortion might be reduced if several straight boards of acrylic were used, resulting in a rectangular tube instead of the circular one used here.

Furthermore, the laser light reflected off of not only the RF electrodes, but mostly the DC electrode, resulting in a reflection on the back of the acrylic tube. This reflection obstructed part of the camera image from detecting spores. Replacing the back of the acrylic tube with some dark cardboard or paper, or even a metal plate might be better. Having a dark background also improves contrast, allowing better visibility of the spores. As said earlier, it is unknown if some spores had entered extended orbits, influencing the ions trapped closer to the center trap axis. A wider laser beam could possibly shed some light on that.

Figure 11 shows one final issue: the noise caused by bright reflections and other spots in the background. An example of this noise can be seen around three thirty p.m. Hence, it is important to shield the trap from outside light sources, especially when using a computer to track the motion of the particles. Operating the trap in a darker room in general also tends to make the ions more easily visible. The measurements on the Coulomb crystals were done early in an afternoon, with a cloudy, yet bright sky outside. This made the lighting in the room fluctuate quite a bit, resulting in LabView having a hard time finding the relatively dimly lit spores. One minute, the image was so dark that very dim 'bright' spots had to be found. Yet, as the sun broke through the clouds briefly, the entire setup would be engulfed in light, polluting the screen with bright streaks. Unfortunately, the blinds in the room were not quite able to block this light fluctuation.

Calibrating measurements in order to convert pixels to $mm$ yielded data points in a nicely straight line, indicating that a direct linear conversion was indeed acceptable. However, this calibration process had to be repeated every time the setup was moved, or had not been in use for a long time, because the

camera was not attached securely to the trapping device. The ion trap sat loosely on top of a table, and the camera was clamped to that table, instead of to the trapping device. Altogether, this is probably not a huge issue with regards to the accuracy of the measurements, as the calibration could simply be repeated after the setup had been disturbed. However, measuring the heights manually was slightly annoying, so it would be nice if this calibration process could be avoided wherever possible. The largest cause of frustration was the fact that some light was needed to actually read the marks on the rulers. This light would then make the spores less visible.
For future projects exploring the mechanics of ion traps by trapping charged moss spores or similar particles, it would be wise to avoid plastics in construction. Most plastic materials can quite easily collect some charge and mess with the field geometry of the trap. Here, that was not so much an issue for the radial fields, but it might be for other trap layouts. Shielding the trapping region from air currents definitely is a must if the trap is to be operated at atmospheric pressure.
It might be better to orient the trap horizontally for demonstrations. In a horizontal setup, the endcap electrodes do not require quite as high a voltage to function. However, gravity would still need to be compensated, now with a much larger electrode. A pair of plates should do. Alternatively, a DC offset on the bottom electrode(s) could be used. The DC voltage used to compensate gravity could even be varied to observe when the trapped ions sit exactly in the center of the trap. In this configuration, a lot of ions could sit on a horizontal line, all of them with the gravitational force balanced by the DC field. This would, however, require the trapped ions to have more similar charge to mass ratios. Ions with higher charge would get pushed up and out of the trap, while lesser-charged particles get ejected from the bottom, as gravity is either over- or under-compensated. Whereas in this vertical trap layout the difference in the charge to mass ratio simply means the ions seek out a different equilibrium point along the central trap axis, but then crystals of ions require some careful balance as they need to stack on top of each other.
All in all, a horizontal trap would probably be better for trapping larger numbers of ions, allowing for more spectacular sights. To this end, it would also be good to set the RF electrodes slightly further apart, and apply a signal with a higher amplitude, potentially up to several $kV$. This would increase the trapping region, as well as allow for ions with a lower $q/m$ to be trapped. It might be interesting to vary the RF and DC voltages to trap particles with a wider range of charge to mass ratios, and to explore different kinds of orbits [14],[18].

# 7 Conclusions

A linear Paul trap was assembled to examine the charge to mass ratio of moss spores. These spores were charged by contact with a statically charged PVC rod. The values for $q/m$ found almost match the values expected from literature, with values between 0.01 $C/kg$ and 0.05 $C/kg$. When a two-ion Coulomb crystal was analysed, a charge around $10^6$ $q_e$ was found. The measurements done here may not be entirely accurate, as the assumed balance of forces might have been disturbed by air currents or stray charges. These external factors sometimes caused ions to drift up or down significantly, regardless of whether the voltage on the DC electrode was changed. This hinted at these irregularities having quite a severe impact on the measurements done. Further, the electric field found in simulations may not be entirely reliable. The uncertainties in the results are also quite large. This, too, is possibly due to the external forces, changing during measurements. All this makes the results found not competely reliable.

For any future spore trapping setups, it is recommended to avoid the use of plastics as construction material. Orienting the trap horizontally may result in an easier time trapping larger numbers of more similar ions. Higher RF voltages would also help to that end. For the visibility of ions, it is advised to operate the trap in a dark room, preferably with a dark background. Using a wider laser beam to make more ions visible is advised.

# References


[1] Wolfgang Paul. “Electromagnetic traps for charged and neutral particles”. In: *Rev. Mod. Phys.* 62 (3 July 1990), pp. 531–540. DOI: 10.1103/RevModPhys.62.531. URL: https://link.aps.org/doi/10.1103/RevModPhys.62.531.

[2] E. Schrödinger. “Are There Quantum Jumps? Part Ii”. In: *British Journal for the Philosophy of Science* 3.11 (1952), pp. 233–242. DOI: 10.1093/bjps/iii.11.233.

[3] D. L. Moehring et al. “Precision lifetime measurements of a single trapped ion with ultrafast laser pulses”. In: *Phys. Rev. A* 73 (2 Feb. 2006), p. 023413. DOI: 10.1103/PhysRevA.73.023413. URL: https://link.aps.org/doi/10.1103/PhysRevA.73.023413.

[4] D. Egorov et al. “Near edge X-ray absorption mass spectrometry of gas phase proteins: the influence of protein size”. In: *Phys. Chem. Chem. Phys.* 18 (37 2016), pp. 26213–26223. DOI: 10.1039/C6CP05254A. URL: http://dx.doi.org/10.1039/C6CP05254A.

[5] H. Häffner, C.F. Roos, and R. Blatt. “Quantum computing with trapped ions”. In: *Physics Reports* 469.4 (2008), pp. 155–203. ISSN: 0370-1573. DOI: https://doi.org/10.1016/j.physrep.2008.09.003. URL: https://www.sciencedirect.com/science/article/pii/S0370157308003463.

[6] Michael Victor Berry. “The Levitron™: an adiabatic trap for spins”. In: *Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* 452.1948 (1996), pp. 1207–1220. DOI: 10.1098/rspa.1996.0062. eprint: https://royalsocietypublishing.org/doi/pdf/10.1098/rspa.1996.0062. URL: https://royalsocietypublishing.org/doi/abs/10.1098/rspa.1996.0062.

[7] R. S. Van Dyck et al. “Variable magnetic bottle for precision geonium experiments”. In: *Review of Scientific Instruments* 57.4 (1986), pp. 593–597. DOI: 10.1063/1.1138875. eprint: https://doi.org/10.1063/1.1138875. URL: https://doi.org/10.1063/1.1138875.

[8] Wayne M Itano et al. “Cooling methods in ion traps”. In: *Physica Scripta* 1995.T59 (Jan. 1995), p. 106. DOI: 10.1088/0031-8949/1995/T59/013. URL: https://dx.doi.org/10.1088/0031-8949/1995/T59/013.

[9] M. Drewsen and A. Brøner. “Harmonic linear Paul trap: Stability diagram and effective potentials”. In: *Phys. Rev. A* 62 (4 Sept. 2000), p. 045401. DOI: 10.1103/PhysRevA.62.045401. URL: https://link.aps.org/doi/10.1103/PhysRevA.62.045401.

[10] A. Drakoudis, M. Söllner, and G. Werth. “Instabilities of ion motion in a linear Paul trap”. In: *International Journal of Mass Spectrometry* 252.1 (2006), pp. 61–68. ISSN: 1387-3806. DOI: https://doi.org/10.1016/j.ijms.2006.02.006. URL: https://www.sciencedirect.com/science/article/pii/S1387380606001047.

[11] B. P. Binks et al. “Naturally Occurring Spore Particles at Planar Fluid Interfaces and in Emulsions”. In: *Langmuir* 21.18 (2005). PMID: 16114917, pp. 8161–8167. DOI: 10.1021/la0513858. eprint: https://doi.org/10.1021/la0513858. URL: https://doi.org/10.1021/la0513858.

[12] Kenneth G. Libbrecht and Eric D. Black. “Improved microparticle electrodynamic ion traps for physics teaching”. In: *American Journal of Physics* 86.7 (2018), pp. 539–558. DOI: 10.1119/1.5034344. eprint: https://doi.org/10.1119/1.5034344. URL: https://doi.org/10.1119/1.5034344.

[13] Richard C. Thompson. “Ion Coulomb crystals”. In: *Contemporary Physics* 56.1 (Jan. 2015), pp. 63–79. DOI: 10.1080/00107514.2014.989715. URL: https://doi.org/10.1080%5C%2F00107514.2014.989715.

[14] A. V. Romanova, I. A. Kosternoi, and Y. V. Rozhdestvensky. “Spatial Confinement of Microobjects in the Radiofrequency Ion Trap in a Viscous Medium”. In: *OPTICS AND SPECTROSCOPY* 128.8 (Aug. 2020), pp. 1292–1297. ISSN: 0030-400X. DOI: 10.1134/S0030400X20080299.

[15] Michael Nasse and Christopher Foot. “Influence of background pressure on the stability region of a Paul trap”. In: *European Journal of Physics* 22.6 (Sept. 2001), p. 563. DOI: 10.1088/0143-0807/22/6/301. URL: https://dx.doi.org/10.1088/0143-0807/22/6/301.

[16] Leah Georgina Wolf. "Trapping lycopodium club moss spores with a radio frequency trap". In: (2021). URL: https://cds.cern.ch/record/2759791.

[17] Bill Lee. *The triboelectric effect series*. Nov. 2022. URL: https://www.alphalabinc.com/triboelectric-series/.

[18] Eugene A. Vinitsky, Eric D. Black, and Kenneth G. Libbrecht. "Particle dynamics in damped nonlinear quadrupole ion traps". In: *American Journal of Physics* 83.4 (2015), pp. 313–319. DOI: 10.1119/1.4902185. eprint: https://doi.org/10.1119/1.4902185. URL: https://doi.org/10.1119/1.4902185.