QUADRUPOLE ION TRAP

STUDENT WORKSHEET

Version 6

en

21/06/18

scool.lab@cern.ch

Warning

When working with quadrupole ion traps you have to follow important safety instructions:

Attention High Voltage

Don’t switch on the power supply until your tutor has checked your setup!

Changes in the wiring must be performed only when switched off.

Only use touch-proof security cables.

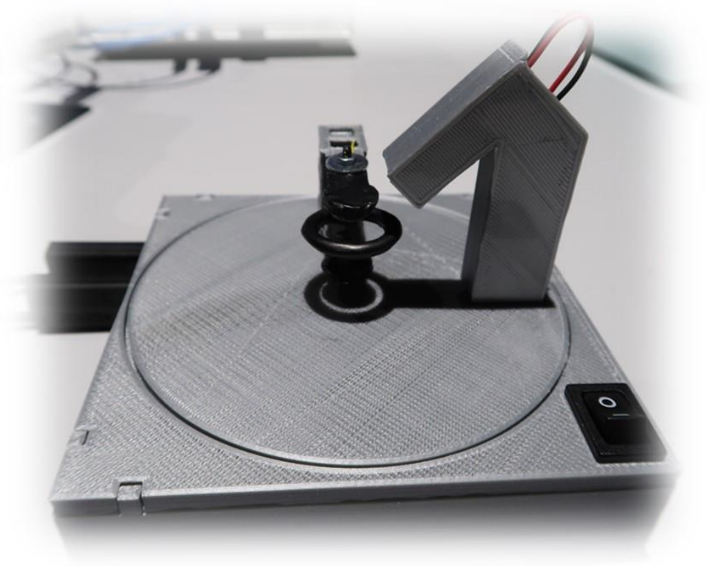
Be aware, that there are two 10 MΩ resistors integrate into your circuit (inside the box) to minimize the current.

Do not touch the electrodes!

Do not destroy the multimeter! That means take out the multimeter for the secondary voltage if you increase the primary voltage over 1 V.

Before switching on, turn all controls and knobs to zero.

Quadrupole ion trap:



Introduction

Your tutor will introduce you to the basics of particle trapping and the details about the equipment used in S'Cool LAB.

Physics

a) What will we trap with the quadrupole ion traps?
b) Why are particle traps interesting for particle physics at CERN?
c) How does an ion trap levitate particles?

Technology

d) What is a transformer and how does it work?
e) What do DC and AC mean?

Now it's time to set up the experiment!

Follow the instructions step by step. Reading them thoroughly will help you to understand what you should do! In the next two steps you will complete the experimental setup and you will complete tasks to ensure you understand the wiring.

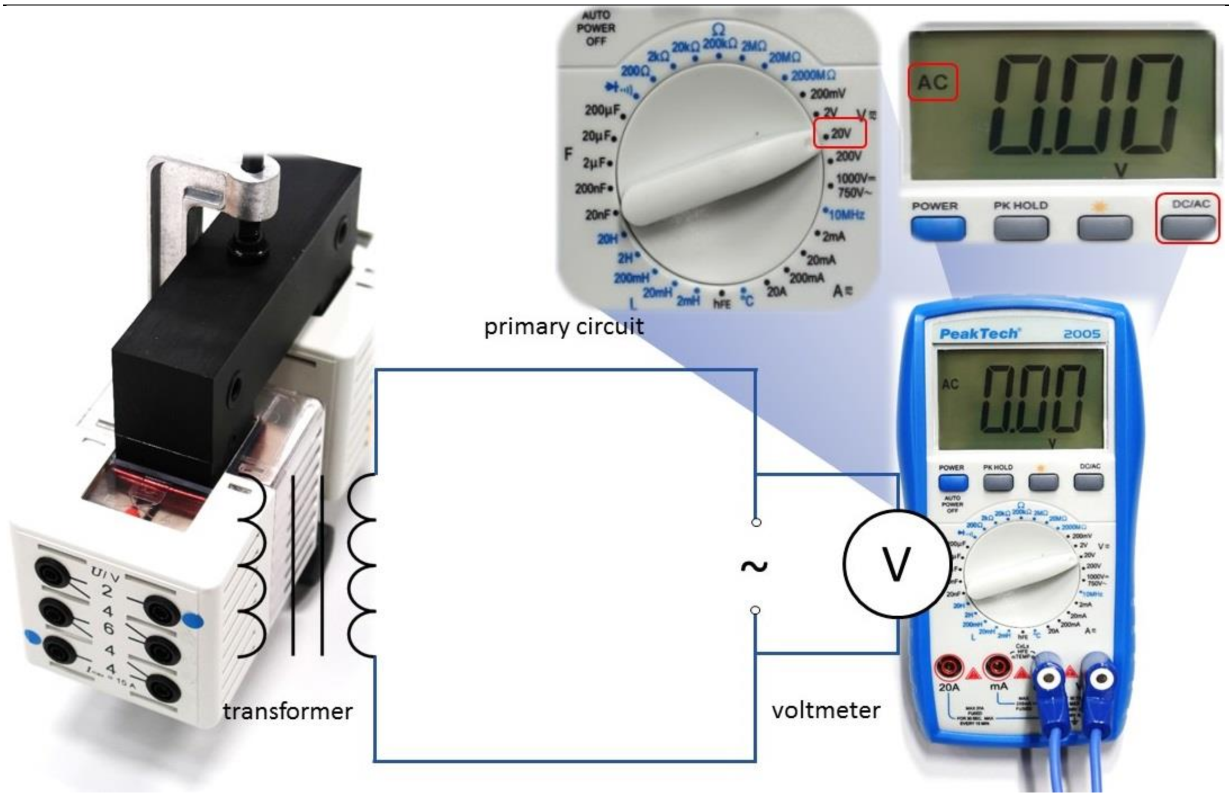
Step 1: Transformer: Produce a high AC voltage
To trap particles with an alternating electric (quadrupole) field, we need very high voltages. Therefore, a transformer is used with a primary voltage of 0 - 20 V AC. This voltage is transformed into high voltage - the secondary voltage - by a certain factor. For our setup, the primary voltage is much lower than the secondary voltage.

Prediction:
Your transformer is equipped with 2 coils: $N_1 = 50,\ N_2 = 10000$.
Which amplification factor do you expect?
(Think about how a transformer works!)

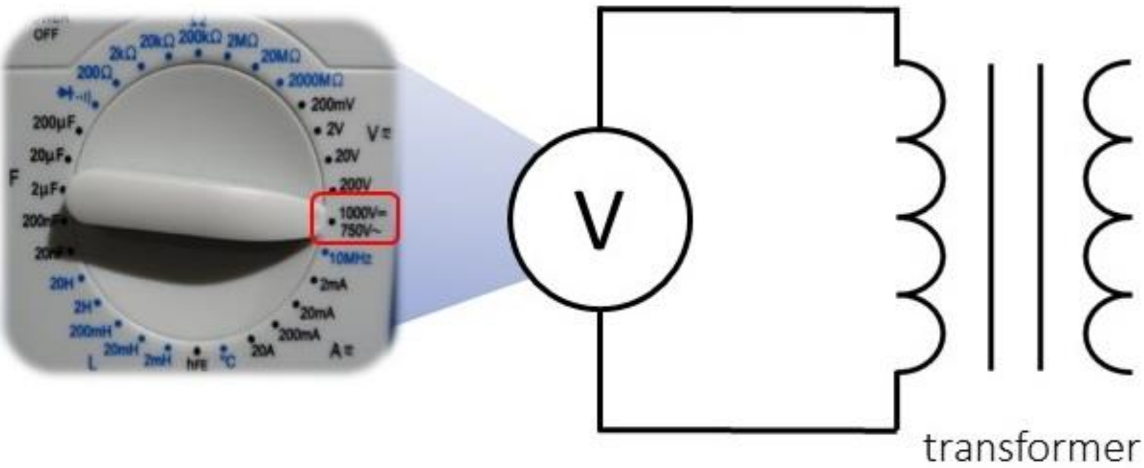
	Student 1	Student 2	Student 3	Student 4
Names:	______	__________	__________	__________
50	☐	☐	☐	☐
20	☐	☐	☐	☐
100	☐	☐	☐	☐
200	☐	☐	☐	☐

Explain your prediction:

Task:
Connect the AC power supply with the primary coil of the transformer (look for 2 blue dots). Connect the voltmeter in parallel to the power supply to monitor the primary voltage.
Don't switch the power supply on!



Task:
Now connect a second voltmeter to monitor the secondary voltage.
Switch on the primary voltage and increase the voltage to 1 V.



S'Cool LAB

Observation:
What is the measured amplification factor of your transformer?

	Student 1	Student 2	Student 3	Student 4
50	☐	☐	☐	☐
20	☐	☐	☐	☐
100	☐	☐	☐	☐
200	☐	☐	☐	☐

Do your predictions match your observation? If not, why not?

Before we start using the trap, it`s important to understand the setup. This is why we`ll introduce you to the common setup of a Quadrupole Ion Trap which uses three electrodes.

For our experiment, we changed the setup a little bit and removed the upper electrode. We`ll have a look at the influence of this change later.

Step 2: Particle trapping – Understand wiring and voltages

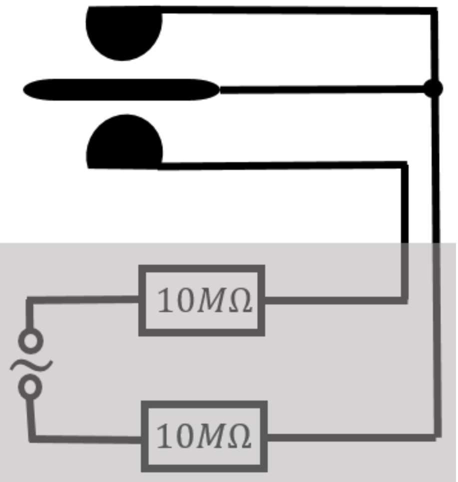
We will apply a voltage between the ring electrode in the middle and the upper and lower electrodes to trap particles. That means that the ring electrode is positively charged if the upper and lower electrodes are negatively charged. When the ring electrode is negative, the upper and lower electrodes are positively charged.

Task A:

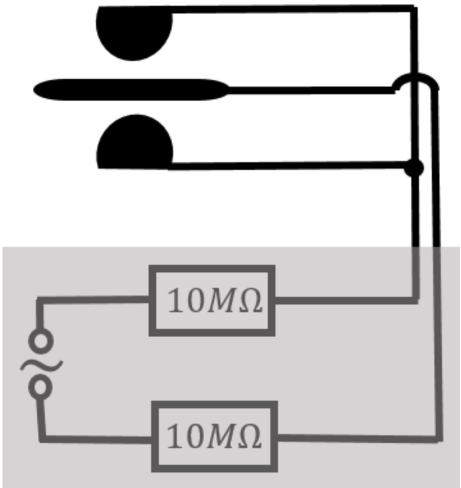
Discuss in your group which sketch represents the wiring of the trap, if you want to have the above described voltage. Choose one of the sketches. After that explain your reasoning to a tutor.

Hint: We need the $10\ M\Omega$ resistors to limit the current (safety first!). If we only have a high voltage but not a high current, it is not dangerous. The resistors are hidden inside the box below the trap.

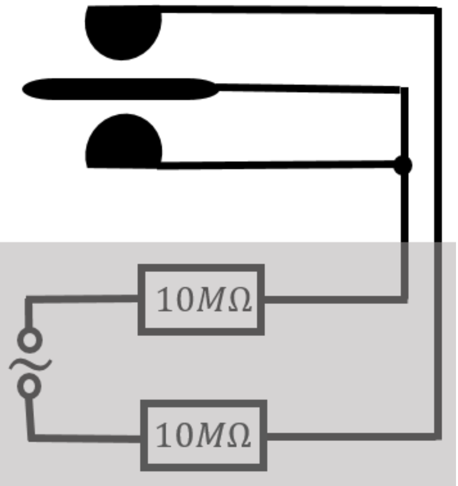
a) ☐



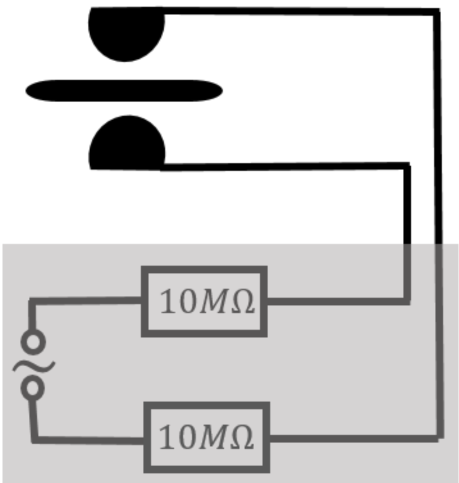
b) ☐



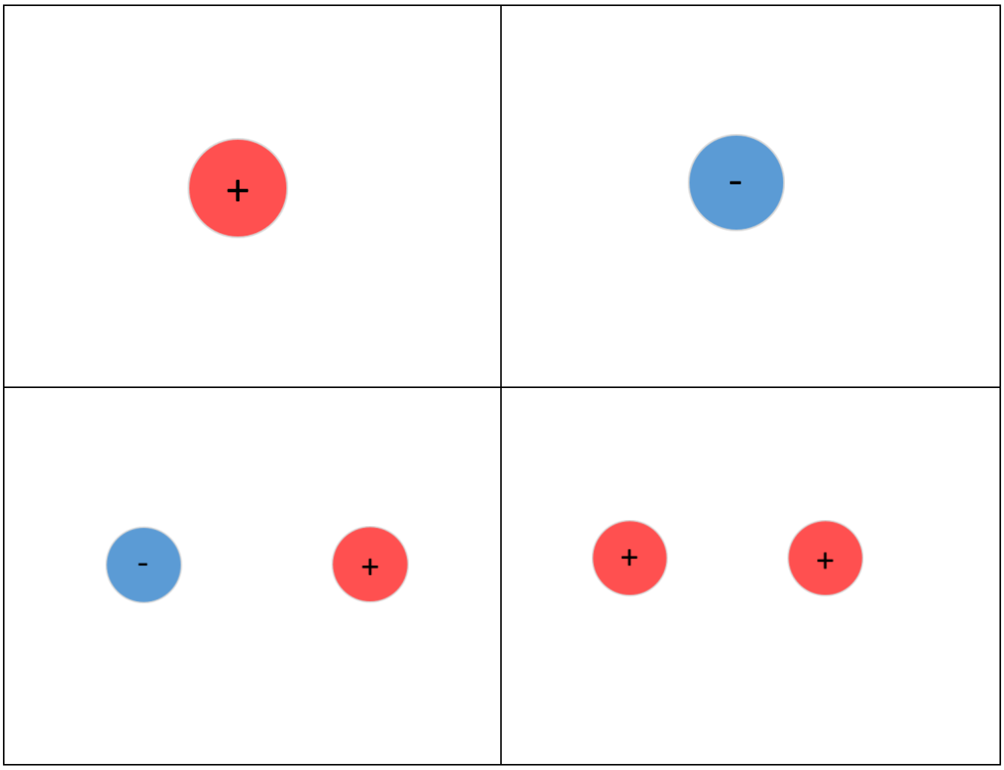
c) ☐



d) ☐

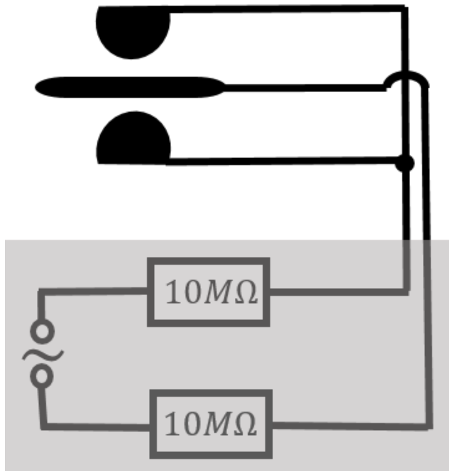


Task C:
Do you remember, how the electric field can be illustrated, using field lines?
First, draw the electric field lines that characterise the electric field of the simple charged particle and the field lines between the two charged particles.

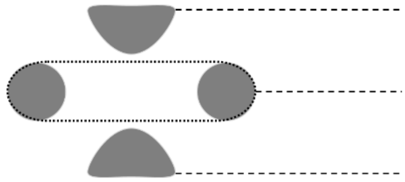


For the following experiment, we`ll concentrate on the area around the electrodes. This is why we`ll use a sketch of the electrodes only, instead of a sketch with the cabling.

Before:

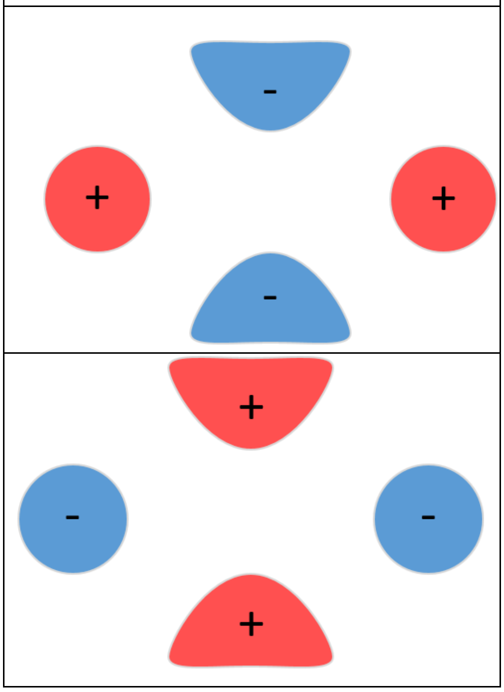


Now:

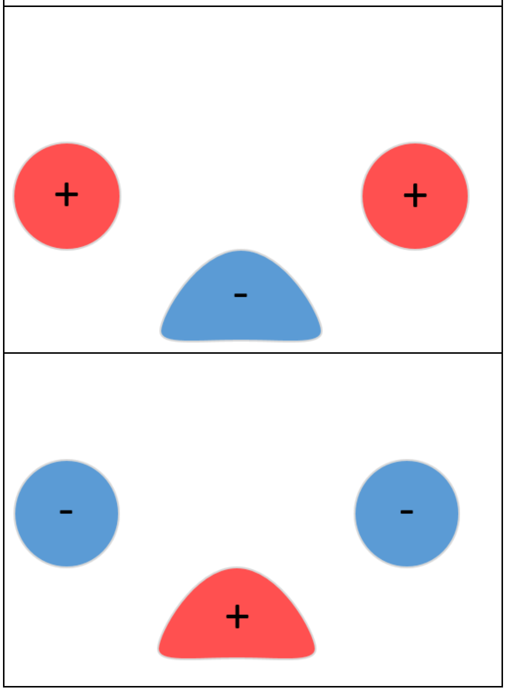


Draw the electric field lines into the sketches of the electrodes of the usual trap and the one you are going to use. Compare the pictures and conclude on what that means for the construction of the trap. We are going to use the colours to show the momentary charge of the electrodes. (Remember, as we use AC voltage the charge will continuously change.)

Trap with upper and lower electrode



Trap with lower electrode only

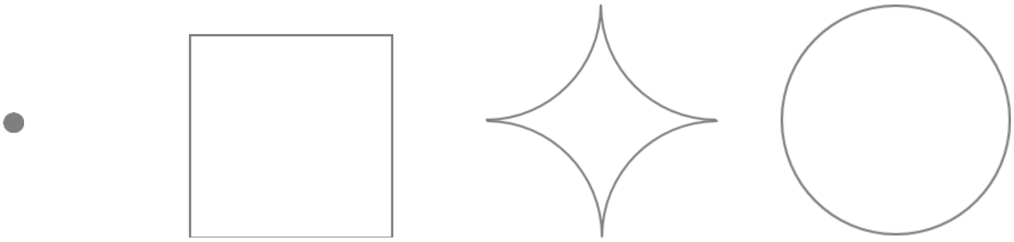


Experiment 1: Trapping the spores
You will now start trapping and see how the spores behave in the trap.

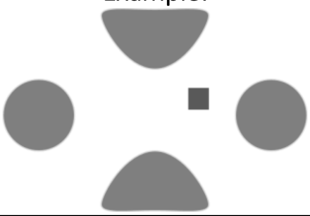
Prediction:
Imagine you place some spores in the centre of the ring electrode. How do you expect them to behave?
Think about how they will be arranged (shape) and where they will be (position).

Decide for one of the **shapes a, b, c, or d** (which are shown bigger than in reality below), and mark the expected **position** of this shape in the sketch of the cross section  below.

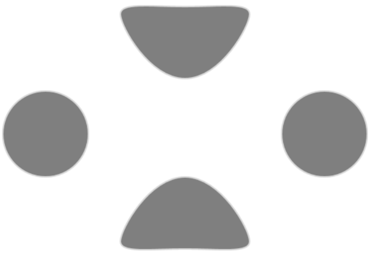
a)	b)	c)	d)
All at one point	rectangular configuration	diamond-shaped configuration	circular configuration



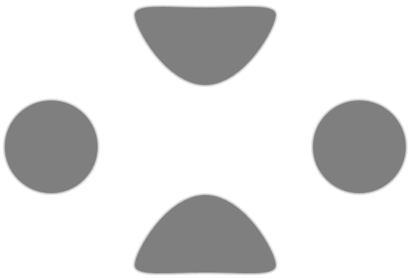
Example:



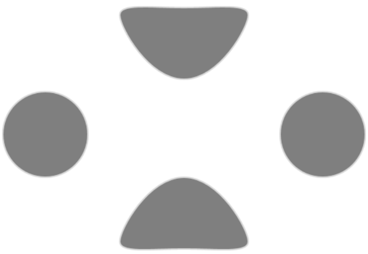
Student 1



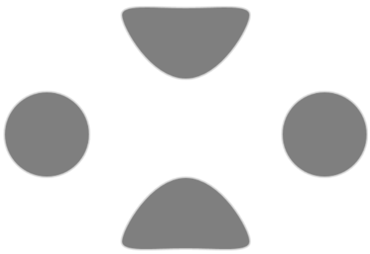
Student 2



Student 3

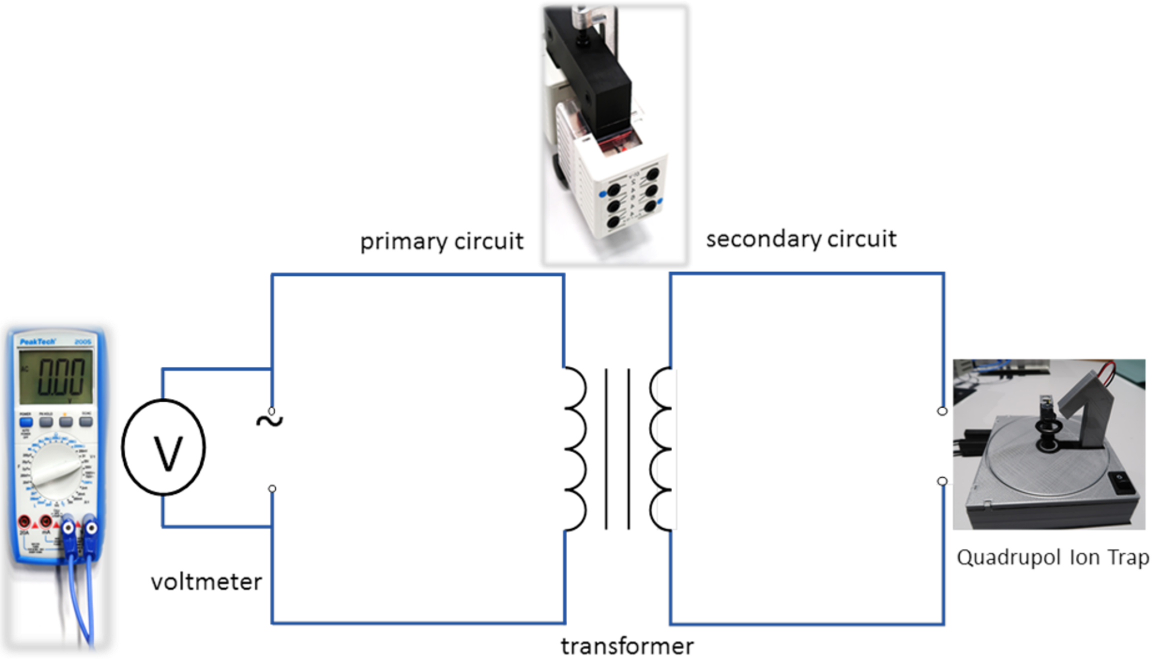


Student 4



Preparation for the next step!

After you discussed your observation, please remove the second multimeter and connect the transformer to the trap instead.
Is the direction of the wiring important? Explain your answer!



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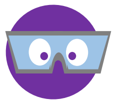
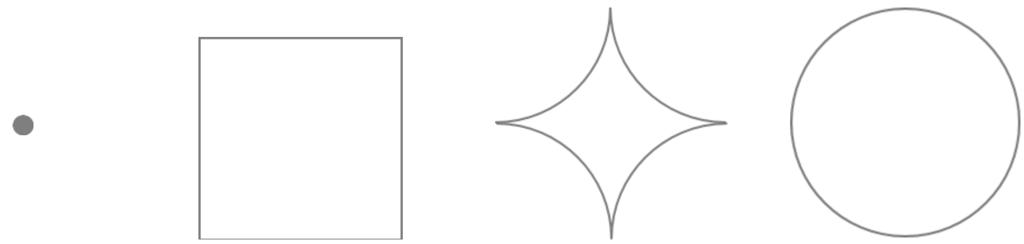


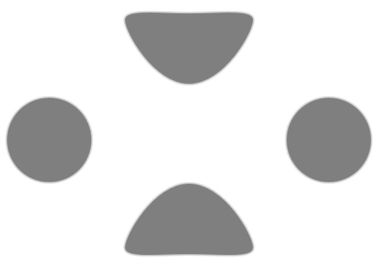
Observation:
Now place some spores in the trap as shown in the introduction, switch on the LED to illuminate them, and find out how they behave.
Information: Each trap has individual settings, so you have to find out on which voltage your trap works best. Try a primary voltage between 10 V and 20 V. (Considering the amplification factor you determined before, this means that you apply a secondary voltage of 2 – 4 kV!)

Decide for one of the **shapes a, b, c, or d** (which are shown bigger than in reality below), and mark the observed **position** of this shape in the sketch of the cross section below.

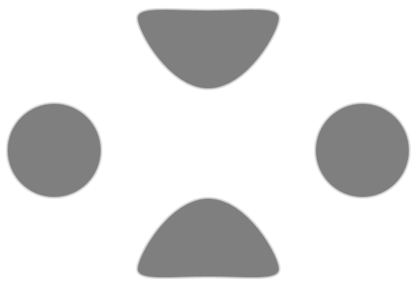
a)	b)	c)	d)
All at one point	rectangular configuration	diamond-shaped configuration	circular configuration



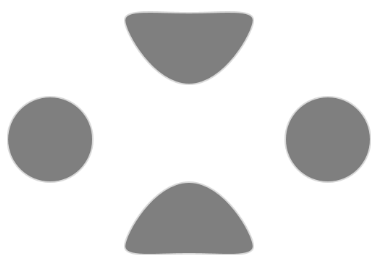
Student 1



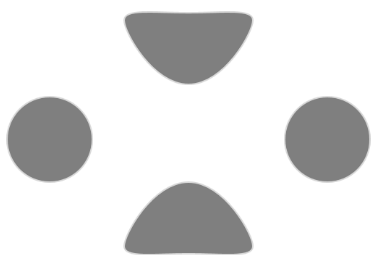
Student 2



Student 3



Student 4

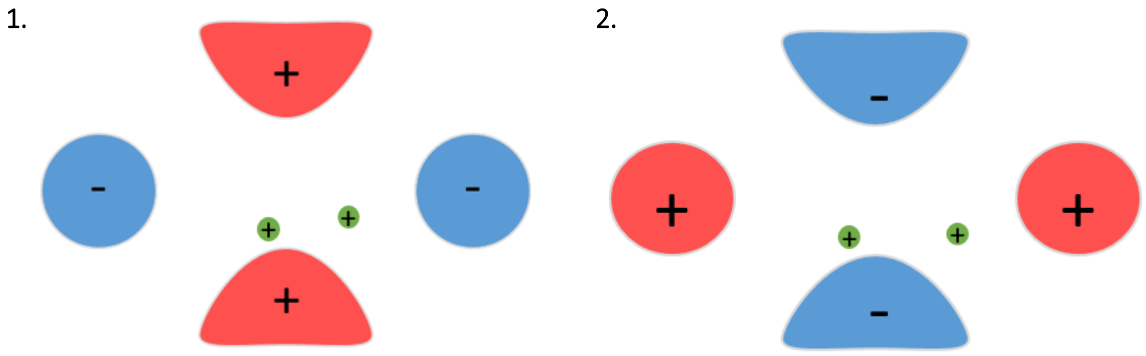


Do your predictions match your observation? Try to explain your observations and answer the following questions:

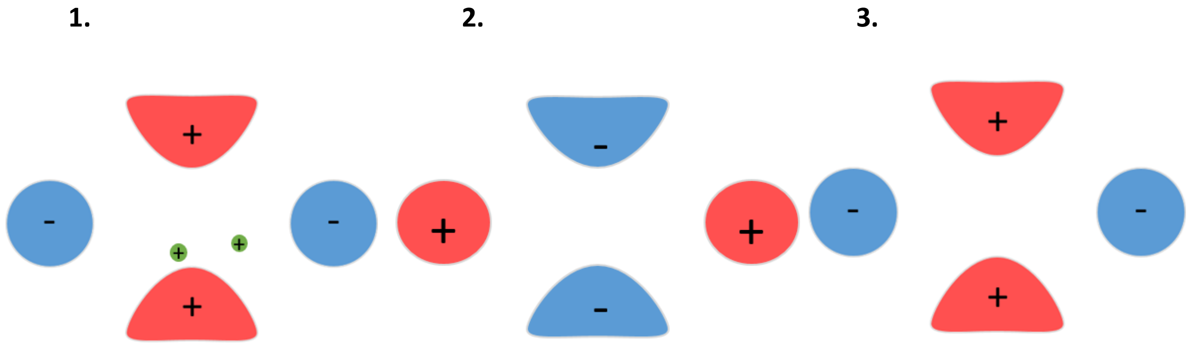
Why is there a certain distance between the spores, and why are they not all clumped together in the centre of the trap?

Discussion:
Now we want to have a closer look at the positive charged spores (Shown here much bigger than in reality). Remember, that we used AC voltage, so the electrodes continuously change their polarity as shown in the 4 pictures below.
Let`s concentrate on just two spores and the influence the continuously changing field has on these spores.

Which effect do the charged electrodes have on the particles? Draw the path of the particles in the following sketches, which show the two different polarisations:



The following three sketches show three changes of polarisation following each other. In the first sketch you can as well find the two spores we want to have a look at.
Draw the path of the particles in the first sketch. Then, draw the new positions of the particles in the second sketch and add as well the path of the spores. Repeat this step for the third sketch.



Use the sketches to explain, why you see lines, not small dots!

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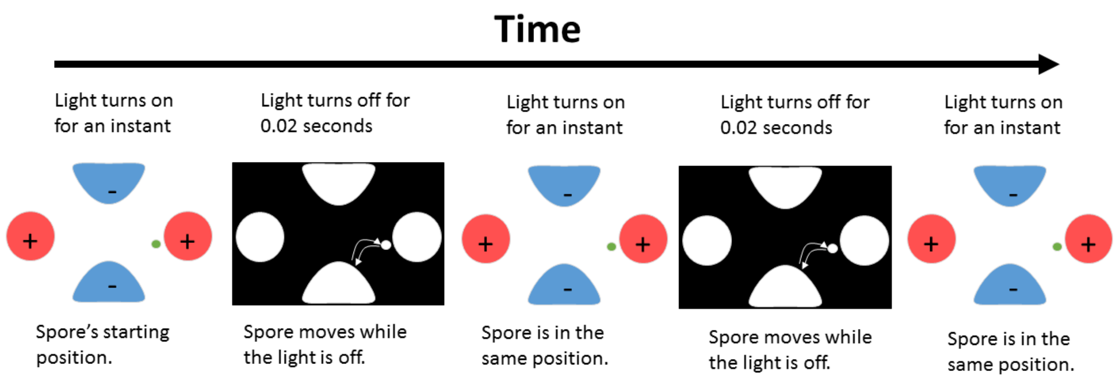
Why are the particles arranged in the shape you have seen?

The Stroboscopic Effect

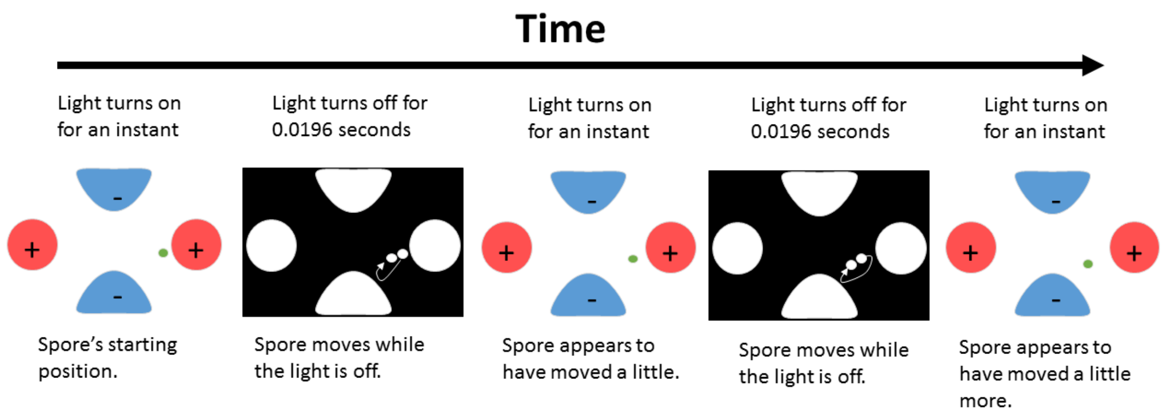
The stroboscopic effect occurs when a continuous cyclical motion is viewed in a series of short, evenly spaced time frames. This can make particles appear to move slowly or even appear to be stationary in the quadrupole ion trap.

Imagine a spore is held in a trap at the position shown in the diagram below. Because it is driven by a 50 Hz electric field, it moves back and forth to its current position in 0.02 seconds. Suppose there is a light that turns on for a very short period of time every 0.02 seconds. Each time the light turns on the spore would be in the same position. This makes it seem that the spore was not moving.



Every time light is on the spore is in the same position.

If the light was flashing slightly faster, say at 51 Hz, the spore would not quite make it back to its original position. So each time the light turns on the spore would be in a slightly different position, making it appear to move slowly.



The overall effect is the spore appears to be moving slowly.

Version 1 (guided inquiry): Experiment 2: The Strobe Effect.
Next you are going to use an LED which strobes. In order to use it, pull the switch the other way.
You can control the frequency at which the LED strobes turning the long black knob.
The frequency available ranges between 30 and 70 Hz.

Prediction:

Make a prediction about what you think will happen when you vary the frequency of the strobing LED. Write your prediction here:

____

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Observation:

Turn on the strobing LED and observe the spores at the slowest flashing speed. Slowly increase the frequency and see how the spores change. Record your observations here.

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Explanation:

Write an explanation of why the spores looked like this. How is it different to what you predicted?

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Challenge:

See if you can make the spores appear stationary! Discuss why this is happening and at which frequency this is happening!

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Version 2 (open inquiry):

Experiment 2: The Strobe Effect.

Next you are going to use an LED which strobes. In order to use it, pull the switch the other way. You can control the frequency at which the LED strobes turning the black long knob.
The frequencies available range between 30 and 70 Hz.

Turn on the strobing LED and observe the spores at the slowest flashing speed. Slowly increase the frequency and see how the spores change. See if you can make the spores appear stationary! Discuss why this is happening and at which frequency this is happening!

Last task: Try to record a video of "dancing spores"!

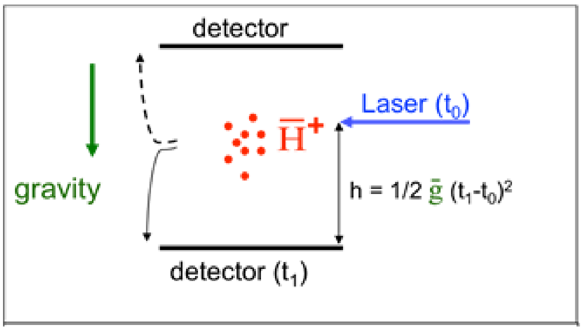
Use your phone to take a video of the spores!
In case you have an USB microscope, like the ones we use in S`Cool LAB, maybe you want to try to use it to record a video and play it in slow motion.

Quadrupole Ion Traps an CERN

Particle traps can be found in various experiments. They are used for mass spectrometry, in atomic frequency and time standards, and in trapped ion quantum computing research. At CERN, particle traps are especially interesting and useful in the "antimatter factory", as they provide a possibility to trap anti-hydrogen ions in order to do further research.

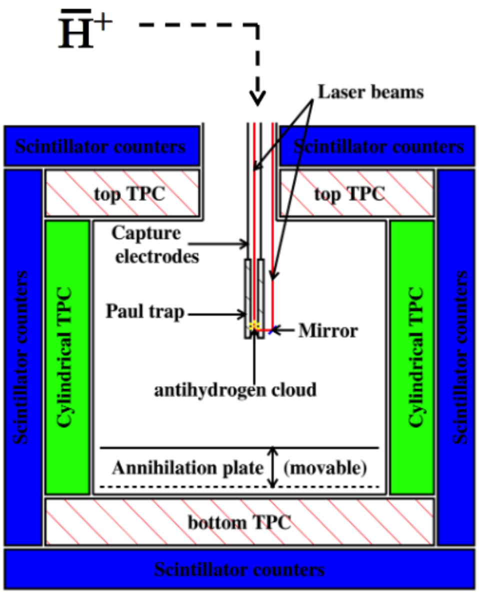
Picture from gbar.web.cern.ch/GBAR/public/en/principle.html

One of the recent experiments is called GBar. Gbar plans to study the gravitational effect on anti-hydrogen atoms. The GBar logo illustrates what the experiment aims to discover: How do anti-hydrogen atoms behave in the gravitational field of the Earth. Do they fall down – or maybe up? To test this, scientists combine an antiproton with two positrons, creating a positively charged anti-hydrogen ion.



Picture from gbar.web.cern.ch/GBAR/public/en/principle.html

Afterwards, the kinetic energy of these ions is decreased, using laser cooling and quadrupole ion traps (sometime called "Paul Traps", after Wolfgang Paul, one of the physicists who developed them). Then, one of the two positrons is detached from the ion using a laser. This process is called "photodetachment". Now the remaining anti-hydrogen atom is electrically neutral and therefore, it cannot be trapped using electric fields anymore. The result is, that the anti-atom starts to fall and it annihilates when it touches matter atoms in the walls of the reaction chamber. Detectors can measure the time the atom needs to fall and the place where it annihilates.



Picture from https://gbar.web.cern.ch/GBAR/results/conf-talks/2015_DPG_Perez.pdf

This is, what the reaction chamber looks like.

By the way, do you know what a quadrupole is?
In principle, it is something with four poles. In our case, the shape of the electric quadrupole field can be describe using four electric charges (2 positive, 2 negative).