QUADRUPOLE ION TRAP

Teacher Manual

Worksheet Solutions and Guidelines

Version 6

en

21/06/18

scool.lab@cern.ch

Warning

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

<u>Attention High Voltage</u>

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.

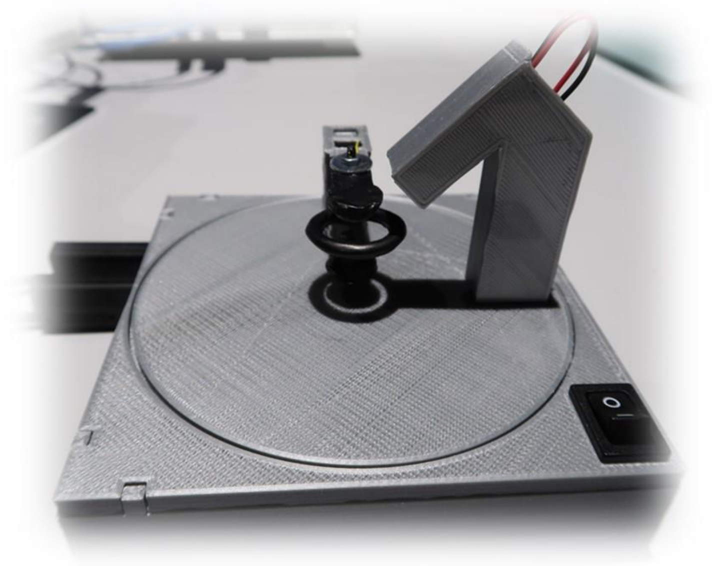
Do not touch the electrodes!

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.

Take care if you have someone with epilepsy in your group. The trap contains a LED with a stobe effect!

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?
Lycopod Spores, have a look at the picture in the appendix. Alternatively, you can use cinnamon powder. Because of friction (triboelectric effect) these spores are electrically charged.

b) Why are particle traps interesting for particle physics at CERN?
It`s used to trap and study antimatter ions (have a look at the infobox on page17 about the GBar experiment)

c) How does an ion trap levitate particles?
Using alternating electrical fields

Technology

d) What is a transformer and how does it work?
It`s a device that adapts the incoming voltage to the required voltage. Induction between two coils with a different number of windings leads to an increased or decreased voltage.

e) What do DC and AC mean?
DC: Direct Current AC: Alternating Current

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.

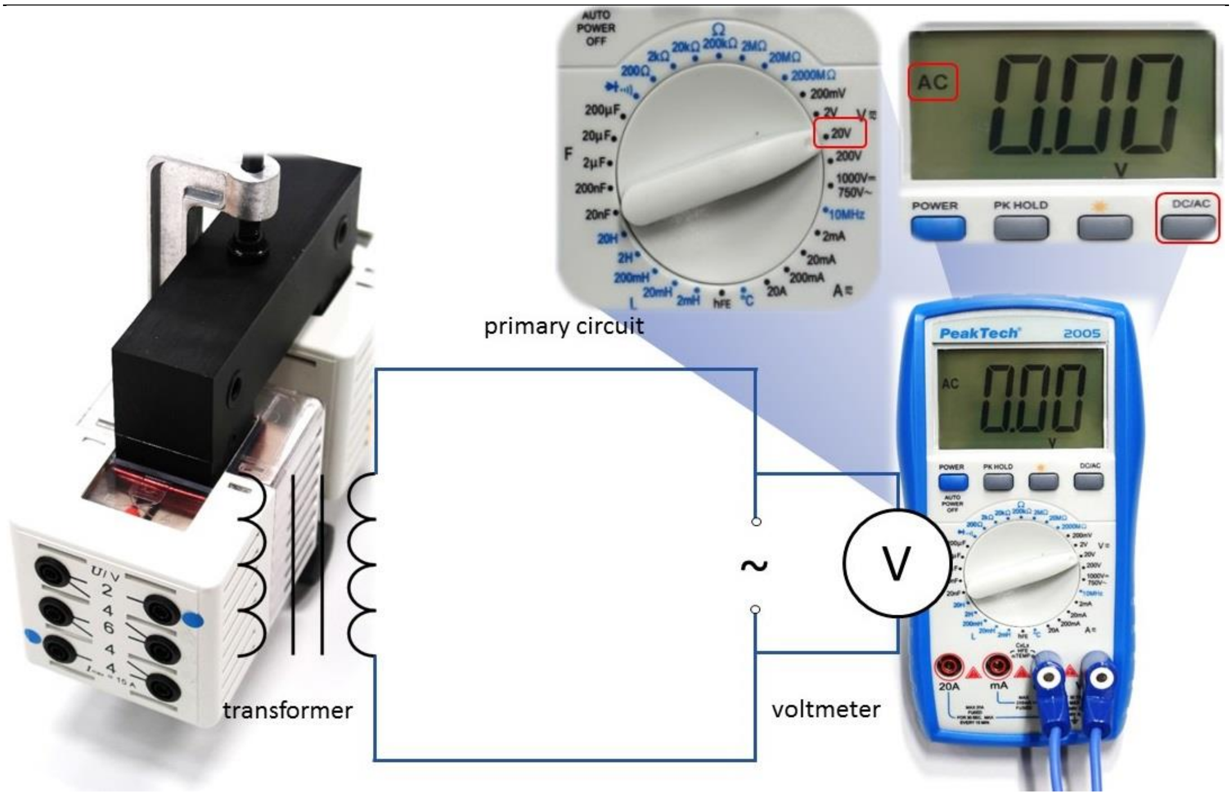
Prediction:
Your transformer is equipped with 2 coils: $N_1 = 50,\ N_2 = 10000$.
Which amplification factor do you expect?
(Think about how a transformer works!)

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

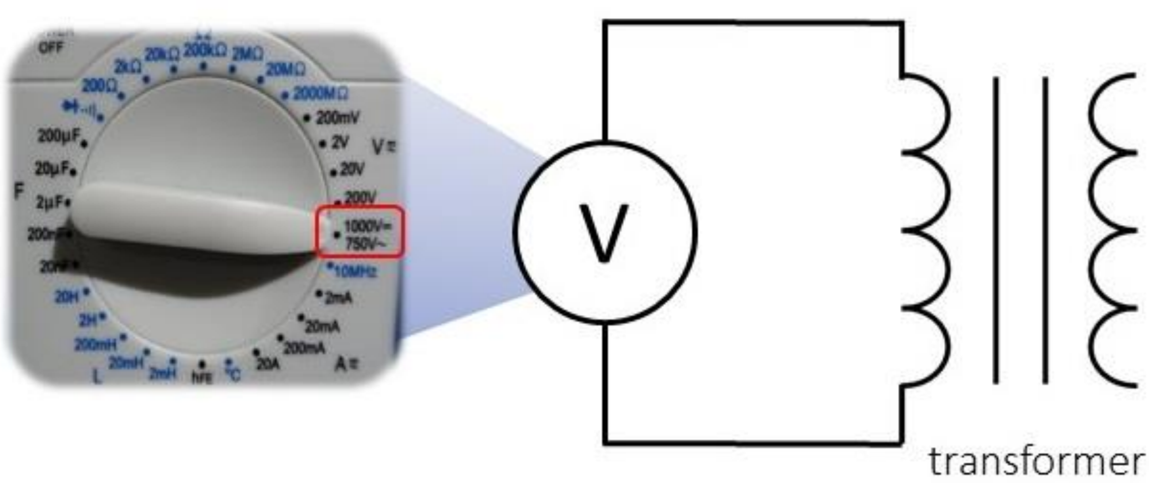
Explain your prediction:

Any prediction is welcome!

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.



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

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

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

$$\frac{N_1}{N_2} = \frac{U_1}{U_2} => U_2 = \frac{N_2}{N_1} \cdot U_1 = 200 \cdot U_1$$

Possible Mistakes: Stepping down the voltage instead of stepping up, …

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.

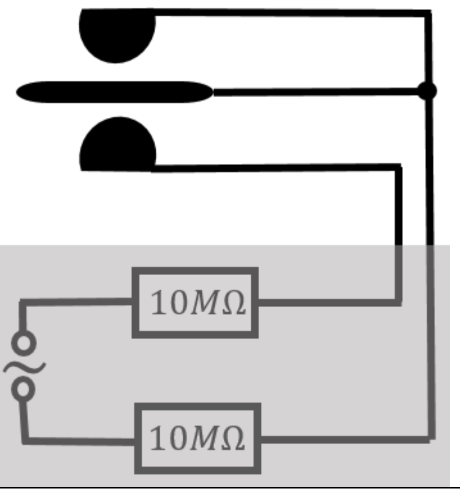
Task A:

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.

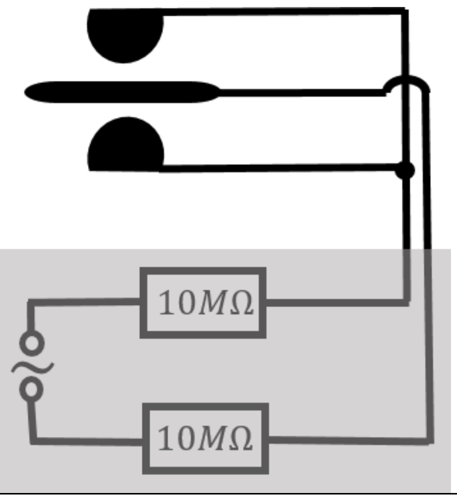
Hint: We need the 10 $M\Omega$ resistors to limit the current (safety first!). If we only have a high voltage but not a high current, it is not dangerous. The resistors are hidden inside the box below the trap.

____

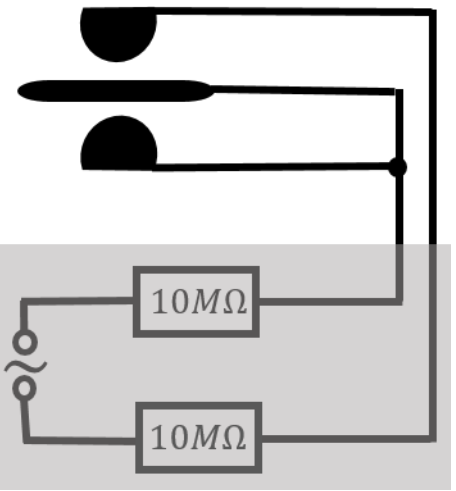
a) ☐



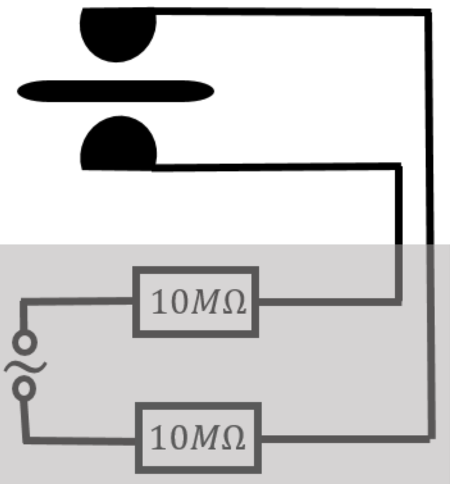
b) X



c) ☐

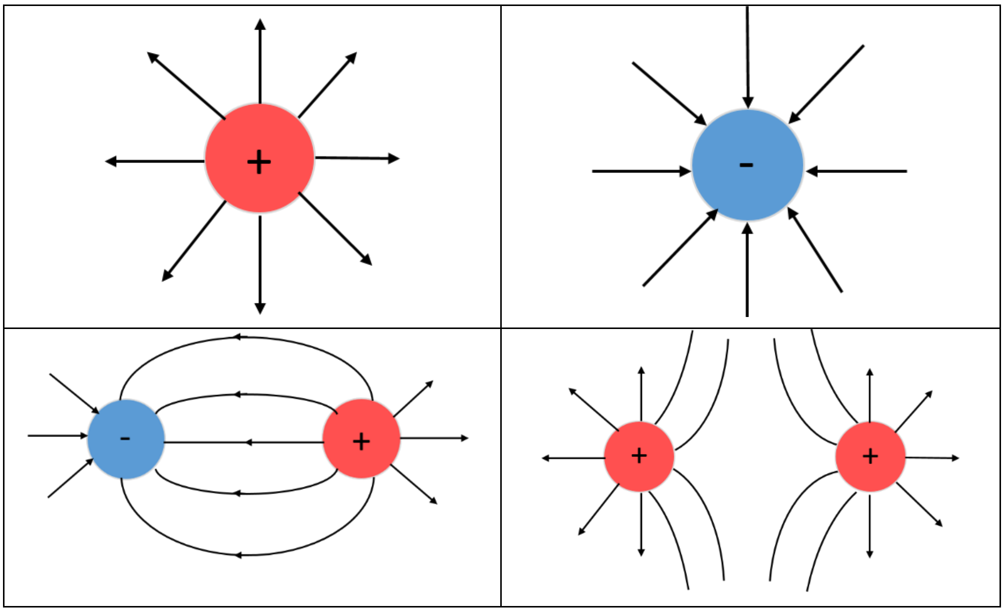


d) ☐

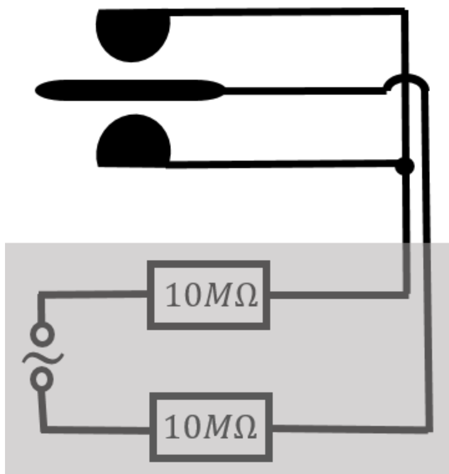
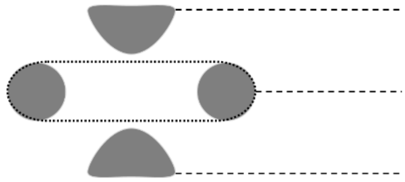


The upper and lower electrode have to have the same electric charge. This is why they have to be connected to the same potential of the DC power supply. The ring electrode is inversely charged, so it is connected to the other potential of the DC power supply.

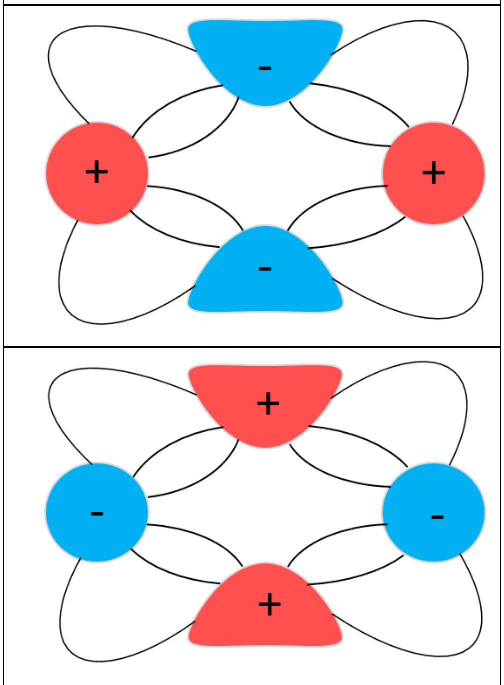
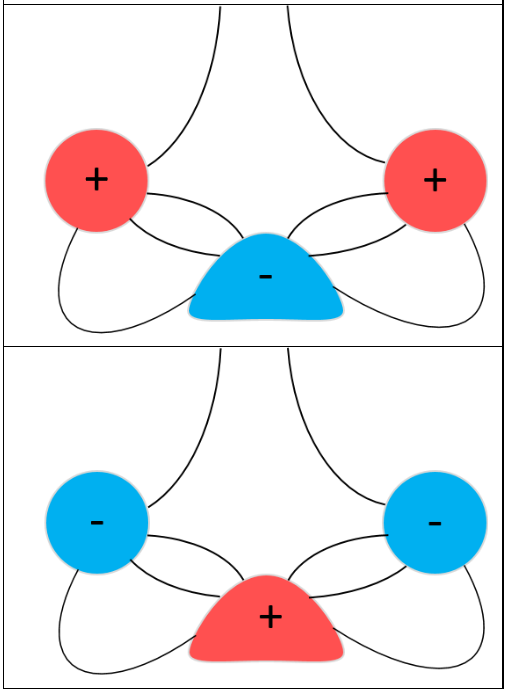
Task C:
Do you remember, how the electric field can be illustrated, using field lines?
First, draw the electric field lines that characterise the electric field of the simple charged particle and the field lines between the two charged particles.



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**
	

In the inner part, between the electrodes, the shape of electric field does not change significantly when the upper electrode is removed. That`s why removing the upper electrode has almost any effect on the experiment.

Experiment 1: Trapping the spores

You will now start trapping and see how the spores behave in the trap.

Prediction:

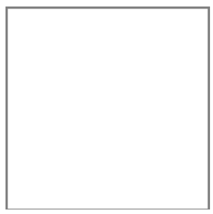
Imagine you place some spores in the centre of the ring electrode. How do you expect them to behave?

Think about how they will be arranged (shape) and where they will be (position).

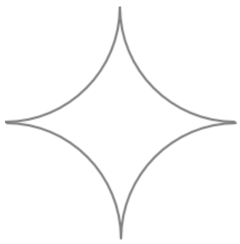
Decide for one of the **shapes a, b, c, or d** (which are shown bigger than in reality below), and mark the expected **position** of this shape in the sketch of the cross section  below.

a) All at one point

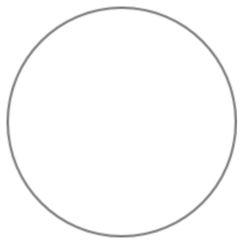
b) rectangular configuration



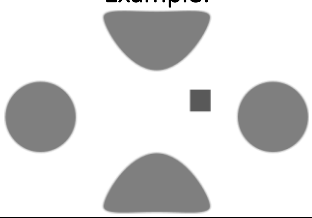
c) diamond-shaped configuration



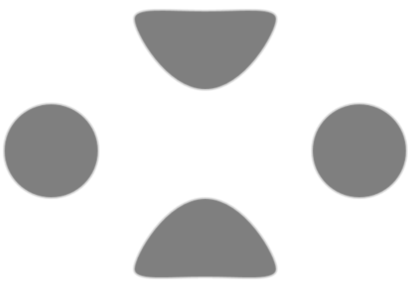
d) circular configuration



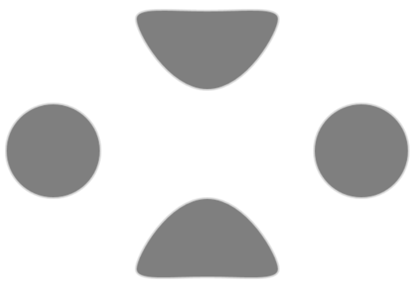
Example:



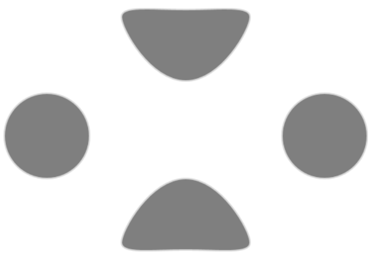
Student 1



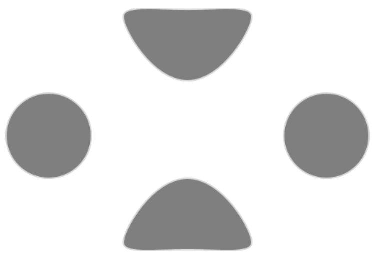
Student 2



Student 3



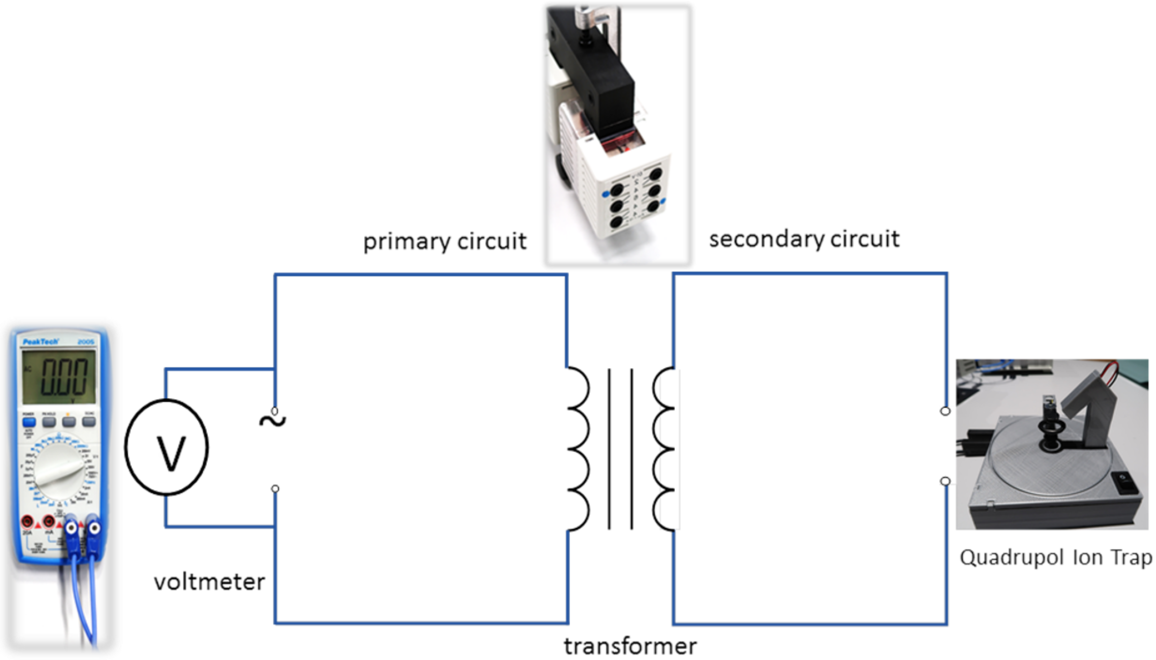
Student 4



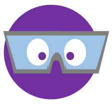
Any prediction is welcome!

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!



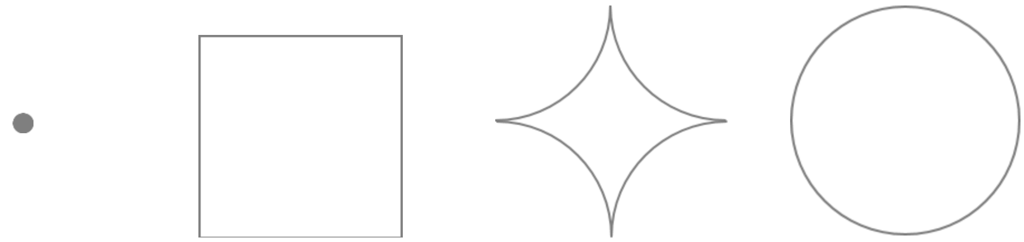
No, the direction of the wiring doesn`t matter because we are using AC voltage. The direction of the electric current changes continuously with a frequency of 50 Hz.



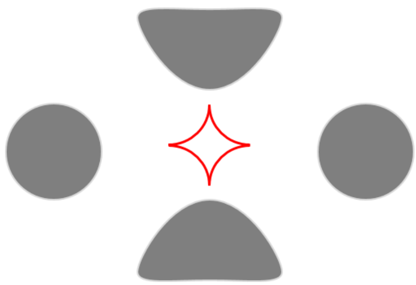
Observation:
Now place some spores in the trap as shown in the introduction, switch on the LED to illuminate them, and find out how they behave.
Information: Each trap has individual settings, so you have to find out on which voltage your trap works best. Try a primary voltage between 10 V and 20 V. (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.

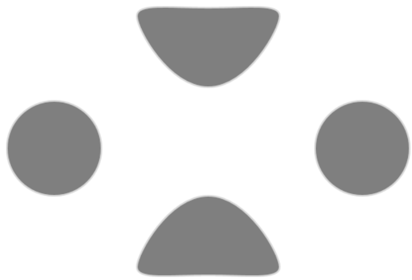
a)	b)	c)	d)
All at one point	rectangular configuration	diamond-shaped configuration	circular configuration



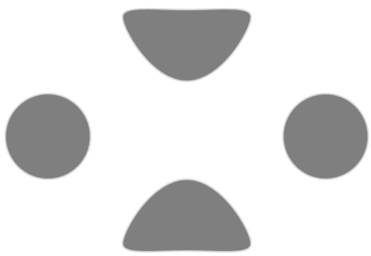
Student 1



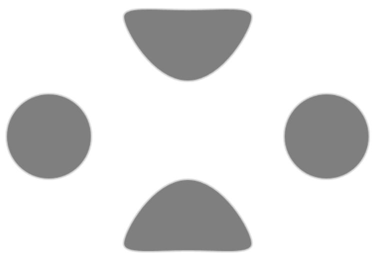
Student 2



Student 3



Student 4



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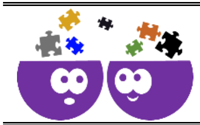

Do your predictions match your observation? Try to explain your observations and answer the following questions:

The spores roughly follow the electric field lines when the move with 50 Hz. Therefore, the exact movement depends on the initial position of the spores. If spores are trapped in the center of the trap (and we ignore the effect of gravity), all forces cancel out and the spores stay where they are.

Other spores move in the electric field. Because a quadrupole field has shape similar to a diamond, and the spores roughly follow the electric field lines when moving with 50 Hz, the cloud of spores appears in a diamond shape.

Because of gravity, this "diamond" is often distorted; sometimes one can only see the lower part.

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

Because of friction (triboelectric effect), the spores are electrically charged. They all have the same charge and repel each other. Therefore, they keep a certain distance away from each other. This effect is sometime called "Coulomb crystal".

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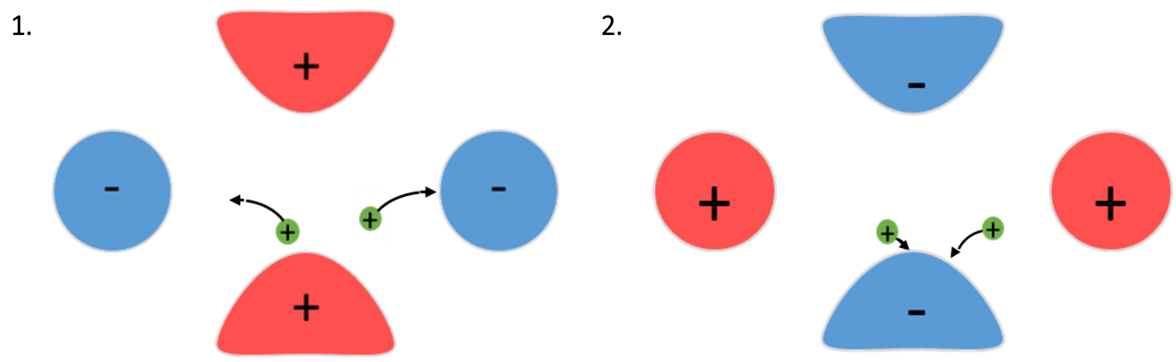
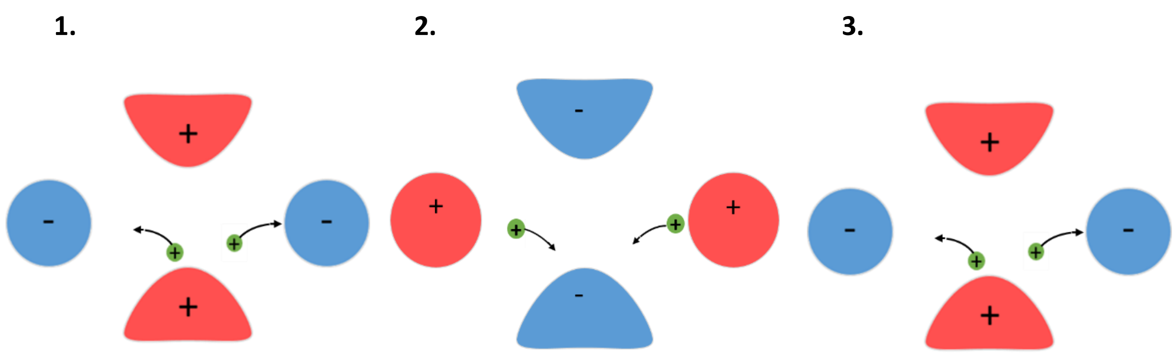
Discussion:
Now we want to have a closer look at the positive charged spores (Shown here much bigger than in reality). Remember, that we used AC voltage, so the electrodes continuously change their polarity as shown in the 4 pictures below.
Let`s concentrate on just two spores and the influence the continuously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

In picture 1 above, the spores are continuously moving towards the negatively charged ring electrode. Whenever the electric charge of the electrodes changes (100 times per second at a frequency of 50 Hz), the spores change the direction of their movement, as they (positively charged) are always attracted by the negative electrode. The particles are moving so quickly (back and forth 50 times per second) that human eyes cannot follow them and they appear as a blur (lines rather than dots). (Nice link: In the film “Now you see Me 2” this effect is used to make rain appear to fall upwards, see: https://www.youtube.com/watch?v=SudyUB9Rzmg).

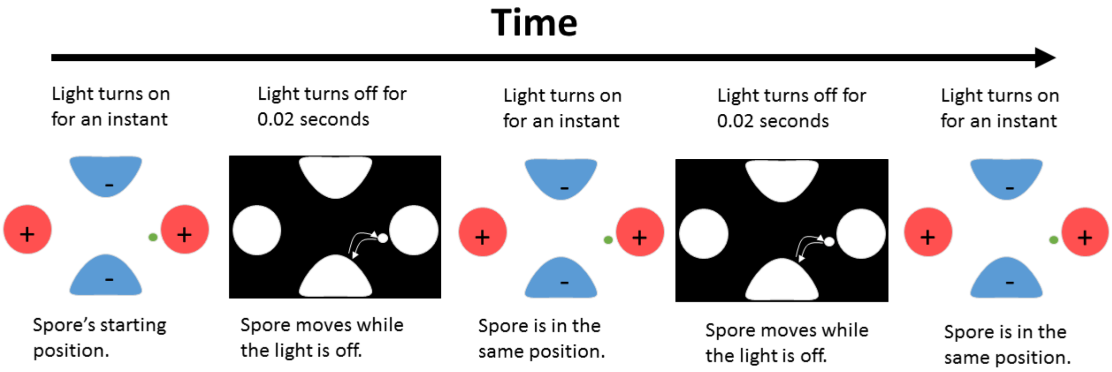
Why are the particles arranged in the shape you have seen?

This is because the spores roughly follow the electric field lines in the trap. Have a look at the field lines, they have a similar shape.

The Stroboscopic Effect

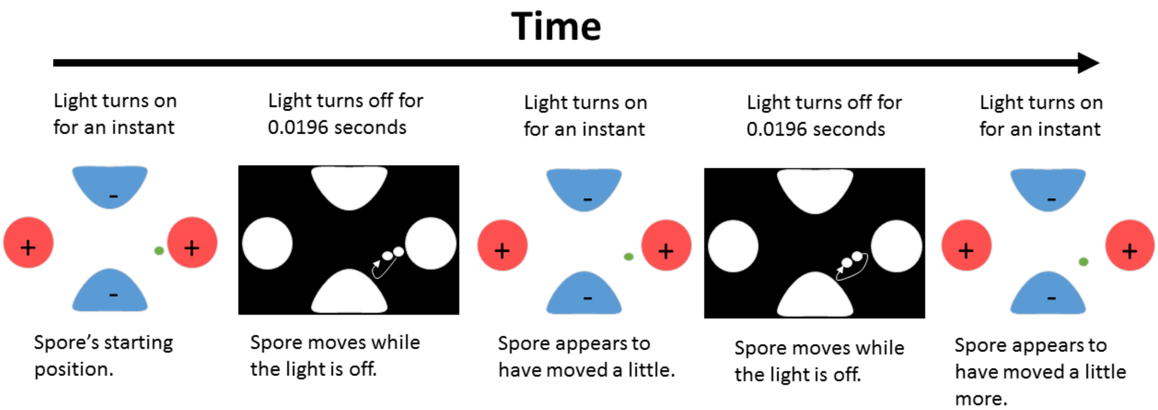
The stroboscopic effect occurs when a continuous cyclical motion is viewed in a series of short, evenly spaced time frames. This can make particles appear to move slowly or even appear to be stationary in the quadrupole ion trap.

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 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:

Any prediction is welcome.

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.

Once the frequency is increased, the lines seem to become shorter. At a frequency of 50 Hz, the spores appear stationary as little dots. If the frequency is increased even more, the lines are getting longer again.

Explanation:

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

With the strobing light, you can only see the spores at the moment when the light is on. Depending on the frequency of the light, the spores travel a different distance between two illuminations. This is the reason, why the lines look longer or shorter.

Challenge:

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

This occurs at a frequency of 50 Hz as the spores will have completed a full movement in both directions and will be illuminated in the same position.

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!

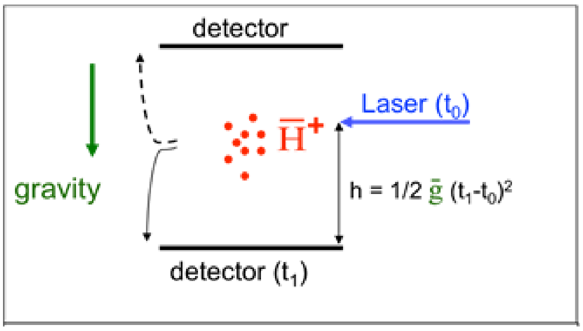
This occurs at a frequency of 50 Hz as the spores will have completed a full movement into both directions and will be illuminated in the same position.

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.

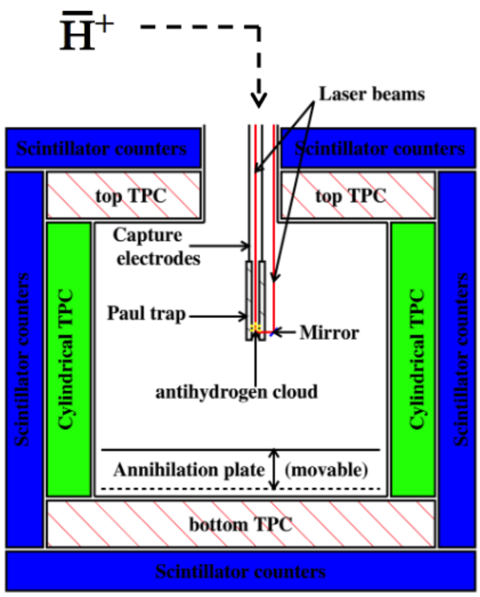
Quadrupole Ion Traps an CERN

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



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



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

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.

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.

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).

Appendix:

Further information, you might want to discuss with your students, before performing the workshop

What we will do today:

- You are going to be an antimatter researcher today. Your task is to learn how to trap particles with a quadrupole ion trap.
- Your "particles" today will not be elementary particles like electrons, but very big particle systems, so called lycopodium spores (show container, show picture). Lycopodium spores look like a fine powder; it consists of very small spores (or seeds). Because of friction, these **spores are electrically charged**.

What is antimatter?

- **Ask students first what they think.**
- Every particle has a corresponding antiparticle – a very important symmetry in the Standard Model of particle physics. Most of their properties are identical, for example, they have the same mass. However, their electric charge is opposite.
- One example is the positron, which is the antiparticle of the electron. The positron has a positive electric charge.
- If a particle meets its antiparticle they annihilate, they are converted, for example, into two photons. The process can be reversed: If there is enough energy, a particle-antiparticle pair can be produced.
- Question: How would you make an anti-hydrogen atom? (take antiproton, add positron)

Why is antimatter research interesting?

- We know that during the Big Bang equal amounts of matter and antimatter particles have been produced (charge conservation law). Today, we only see matter around us, the antimatter has disappeared.
- We need to study antimatter, to find out if there are maybe small differences between particle and antiparticles that could explain, why we live in a "matter world". Or maybe there is an antimatter world somewhere far away in the universe?

What kind of antimatter experiments are we doing at CERN?

- One of the many experiments is called GBAR.
- It will try to answer a very simple – but exiting question: Imagine you drop a matter apple on our matter Earth. Everyone agrees, that it will fall down. Now, imagine you drop an antimatter apple on an antimatter Earth. What will happen? Everyone agrees, that the same physics rules would apply, so the apple would fall down. (In fact, if we had a switch that could turn all the matter into antimatter, we wouldn't notice any difference).
- Now the exiting question: If you drop an antimatter apple on our matter Earth, will it fall UP or DOWN? Who thinks it would fall upwards? Who thinks downwards? Who thinks it wouldn't move at all?
- Most physicist believe, it would fall down, but we have never done this experiment!
- Because an antimatter apple is a very complex system, at CERN we use the most simple particle system: an antihydrogen atom
- GBAR will therefore first trap antihydrogen and then do a freefall experiment with it.
    - Question: Why do you we need to trap the antihydrogen atoms first?

Imagine you want to trap 10 anti-hydrogen ions in your lab. With which forces might you trap the particles?

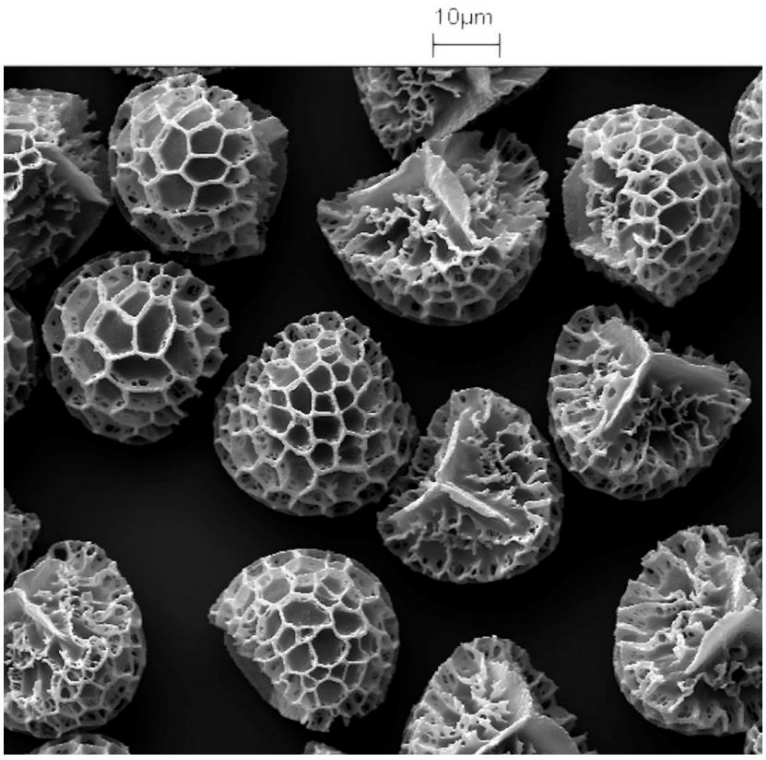
- Let students discuss first.
- We use electrical fields. Do you know what that is? Have you heard about electrical field lines?
- Show them a picture of two positive charged spheres and let them draw the electric field lines of those two spheres. Ask them about the force that affects a positive charged particle.

Can you imagine another component, which is especially important for antimatter traps?

- components: vacuum (otherwise they annihilate with air molecules), force to keep them together in all directions (they all have the same electric charge)

Lycopodium plant and spores
(these pictures can be printed and laminated in order to show them to the students)

Lycopodium serratum (Lycopodiaceae) © Keisotyo / Wikimedia Commons /



Scanning electron microscopy (SEM) picture of Lycopodium clavatum spores showing homogeneity of size and morphology. Diego-Taboada, A.; Beckett, S.T.; Atkin, S.L.; Mackenzie, G. Hollow Pollen Shells to Enhance Drug Delivery. *Pharmaceutics* **2014**, *6*, 80-96.

Further suggestions on how this workshop can be extended to a project.

1) It is possible for students to build the traps themselves. There is an instruction manual available on Zeonodo: DOI 10.5281/zenodo.1251787
By doing this, the students will get familiar with electric circuits and the components needed for building the trap. The circuit contains resistors, diodes and LEDs and uses a potentiometer to change the frequency of the strobing LED.
2) This experiment is links to electric fields and transformers, both are frequently a part of the high school curriculum. It also offers the opportunity to discuss antimatter and the cutting edge research.
3) We used the programme FRITZING in order to create our circuit diagrams and breadboard schematics. This freeware programme offers the opportunity to create circuit diagrams and transform the diagram into a breadboard schematic. You can use the software to test the connections in the circuit. This software shows students pictures of the components and the circuit diagram symbols used for the different components.