Misbehaving Electrostatics I

PETER ŽILAVÝ

Department of Physics Education, MFF UK

In school experiments in electrostatics and in many activities in everyday life, bodies are often charged or discharged by means of short electric discharges. What is happening during charging of a metal body or a school electroscope by an electrified rod? How to look for a mistake when something doesn't work? An unusual way to find answers to these questions using a digital oscilloscope is the subject of this contribution.

Introduction

To find out if (and how) a body is charged, we usually use an electroscope or some electronic instrument or indicator of electric charge. Charged bodies also attract uncharged pieces of paper, hair or other small objects (e.g. due to their polarization and subsequent attraction in an inhomogeneous field of the charged body).

The operation principle of electroscope (electrometer) lies in mutual repulsion of parts with the same electric charge. Electronic charge indicators use a measuring capacitor (with a significantly larger capacity than the examined metal body) with one grounded electrode. After connecting the second pole of the capacitor to the body, the capacitor is charged with the same electric charge as the body. The charge can then be determined from the voltage on the capacitor and its capacity. This principle is described in detail in [1].

If we conductively connect the charged body with the ground, we dissipate its charge (only a part of its charge in the case of a body made of insulator) into the ground. During this connection, electric current flows for a while. The size and duration of this "current pulse" depends on the capacity of the body (size, shape, …) and on the overall resistance of the connection with ground. In the following text, the connection with ground will be represented by a high-voltage (hereinafter referred to as "HV") oscilloscope probe.

Oscilloscope and High Voltage Probe

We usually use an oscilloscope to display the time dependency of electrical quantities in low-current circuits. Joined with a high voltage probe, however, it may be a useful tool for electrostatics. A digital oscilloscope (nowadays easily available) is suitable for this use, enabling capturing, displaying and measuring of one-time events (peaks, individual pulses). The description of how to operate an oscilloscope is not the subject of this article, basic information can be found, for example, in [2].

Standard voltage ranges of the oscilloscope can be increased by using a suitable probe (which combined with the oscilloscope input represents a frequency-independent voltage divider). In our experiments, we used a high-voltage probe 1000x allowing a safe voltage measurement at the tip of up to 40 kV. From the point of view of the body to which the probe is approached, the probe with the oscilloscope can be replaced by a parallel combination of a resistor with a resistance of 100 MΩ and a capacitor with a capacity of about 3 pF connected to ground.

Fig. 1. Oscilloscope and high voltage probe

The output information is potential (voltage to ground) curve of the probe tip or rather the time potential curve of the body to which the probe is connected.

What Will We Need?

For the following experiments, we will need an oscilloscope with a high voltage probe and: PVC rod (waste pipe or vacuum cleaner tube), glass rod, flannel cloth, artificial buckskin and a piece of skin to rub the rods with, laboratory stand with clamp to attach the high voltage probe, metal ball on an insulating stand, larger metal ball taken from a school Van de Graaff generator, and connecting wires with a banana plug.

Fig. 2. Equipment for experiments

Discharge of a Charged PVC Rod

The following section will examine the discharging of electrified rod into metal bodies of different dimensions – the tip of the probe, the ball placed on the probe tip and into the other two larger balls attached to the oscilloscope probe.

First, we gradually move the charged PVC rod closer to the sharp tip of the HV probe. As it gradually approaches, we observe a number of pulses on the oscilloscope screen at a distance of a few centimetres from the tip of the probe – the rod discharges into the tip. The impulses have a negative polarity, a negative charge bursts from the rod. It confirms the known saying that a PVC rod rubbed with flannel or synthetic buckskin is charged negatively.

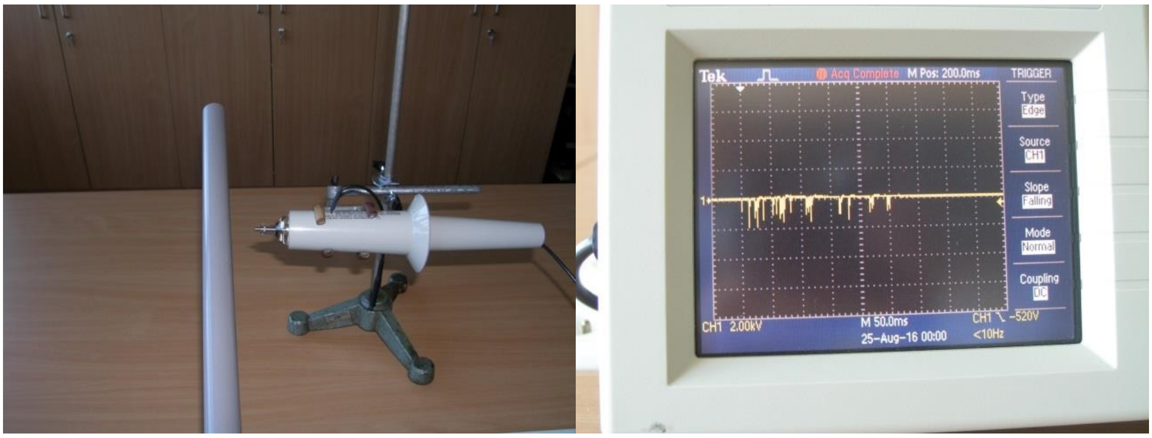

Fig. 3. Bursting of charge from a charged PVC rod into the probe tip

If we move the rod in the direction of its axis at an unchanged distance from the probe, another charge will burst into the tip (we see another series of pulses on the oscilloscope screen. Thus, only a part of the charge from a small area of the charged insulator rod discharges into the probe tip. Later, this fact will allow us a detailed examination of charged bodies made of insulator such as the belt or pulleys of a school Van de Graaff generator.

We now move the charged PVC rod closer to the HV probe with a metal ball with a diameter of 18 mm attach to its tip.

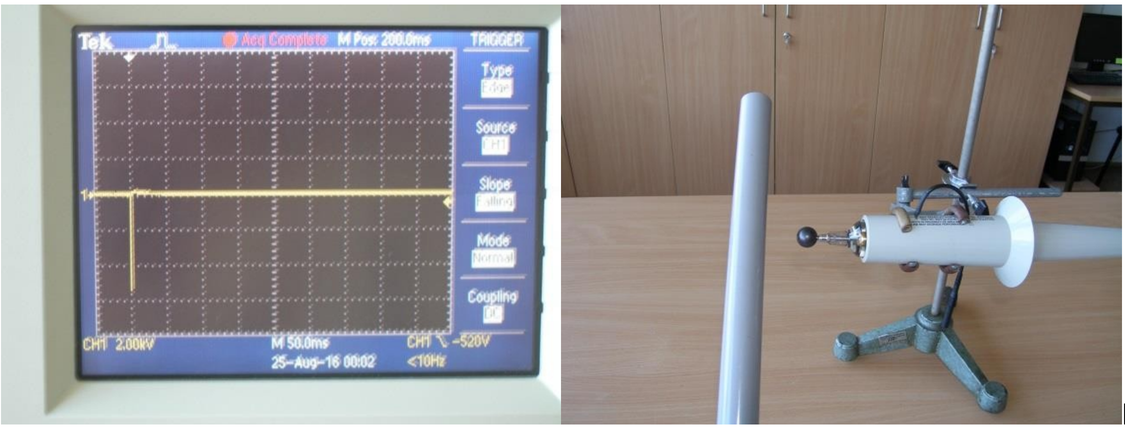

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Fig. 4. Discharge into a ball attached to the probe tip

The charge bursts into the probe at closer distance than in the previous case. Let's look more closely on the pulse recorded by the oscilloscope in higher time resolution (1 ms/section). The amplitude of the pulse is worth attention first. With a set range of 2 kV/section, it represents a value exceeding 8 kV. This value represents the lower potential estimation of the place of the charged rod from which the charge burst.

From the voltage curve pulse, it can be seen that the actual "jump" of the charge from the rod to the ball (steep edge of the pulse) occurred in much shorter time than 1 ms. The "finish" of the pulse in the order of ones of milliseconds is then caused by the subsequent discharge of the ball, tip and inner parts of the probe through the resistance of the probe into the ground. Time constant $\tau = R \cdot C$ that is approximately 0.6 ms very well agrees with the probe resistance of 100 MΩ and the capacity of the ball and inner parts of the probe in the order of pF.

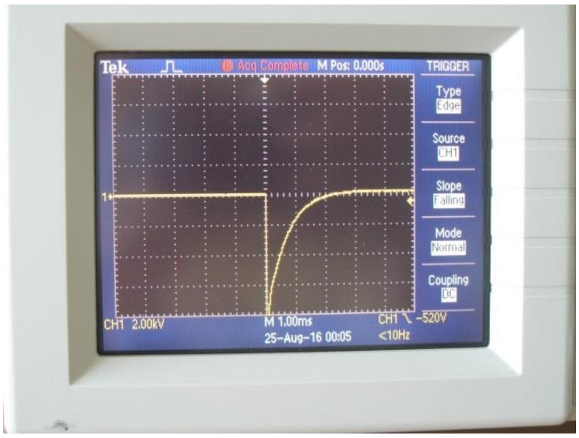

Fig. 5. Potential curve of the probe tip at a higher time resolution

We will now adjust the arrangement of the experiment so that a metal ball with a diameter of 8 cm or a large Van de Graaf generator ball is placed on an insulating stand between the rod and the probe in such a way that it touches the tip of the probe. Then we start to move the rod closer to the ball.

Fig. 6. Discharge of the rod into a metal ball attached to the probe tip

The amplitude of the pulse is now slightly smaller than in the case of a small ball, the "finish" of the discharge is significantly prolonged.

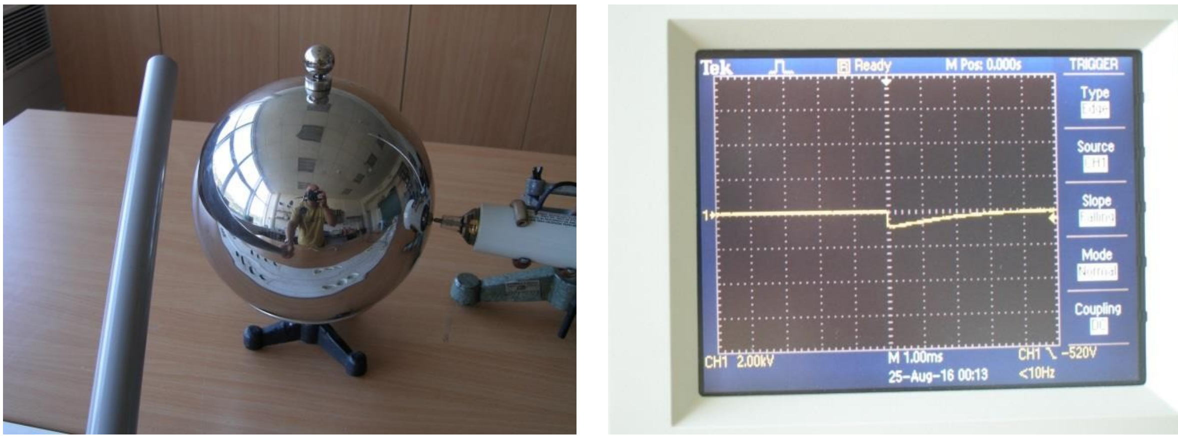

Fig. 7. Discharge of the rod into a large metal ball attached to the probe tip

In the case of a large ball, the amplitude of the pulse is even smaller than in the previous case, the "finish" of the impulse is even longer. This can be seen better from Fig. 8 when setting a smaller voltage range on the oscilloscope.

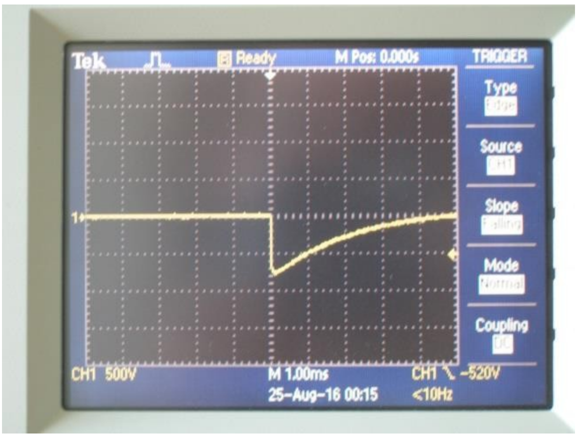

Fig. 8. The potential curve of a large sphere attached to the tip of the probe

The decrease of the leading edge of the pulse and its elongation are caused by the larger capacity of the sphere compared to the small ball at the beginning of this experiment (the capacity of a sphere is directly proportional to its radius). The charge that was discharged from a particular part of charged PVC rod into the sphere caused the charging of the ball to a lower potential than it was in the case of small ball due to larger capacity. Thanks to the larger capacity of the ball, the discharge time constant has also been extended.

Discharge of a Glass Rod

We will now repeat the introductory experiment from the previous paragraph with a glass rod charged by rubbing it with a piece of leather. We gradually bring the charged rod closer to the sharp tip of the HV probe.

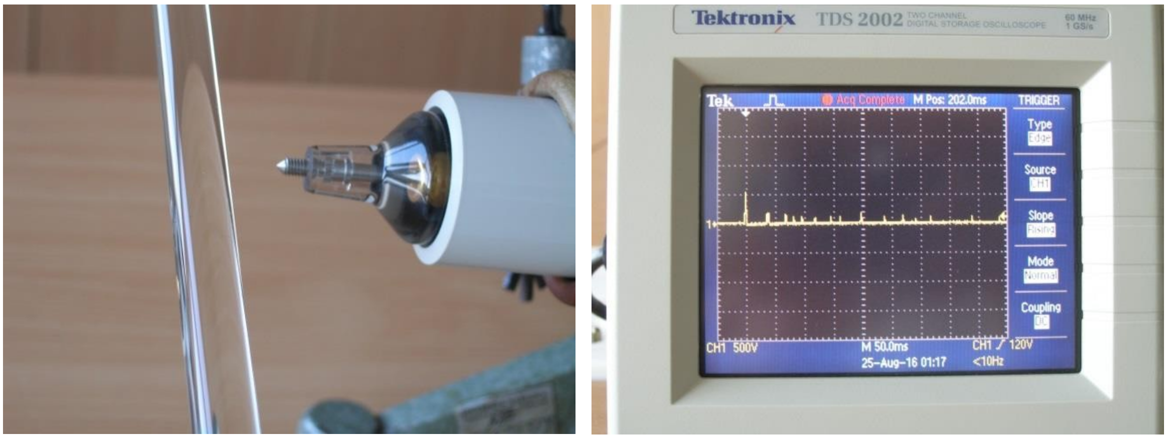

Fig. 9. Charge bursting from a charged glass rod into the tip of the probe

As in the case PVC rod, with glass rod we can observe a series of pulses on the oscilloscope display when we gradually move the rod closer to the tip of the probe. However, the polarity of these pulses is positive, positive charge bursts from the glass rod; rubbing a glass rod with leather creates a positive charge on the rod.

Now we approach the charged glass rod with the HV probe with a small metal ball with a diameter of 18 mm attached to it.

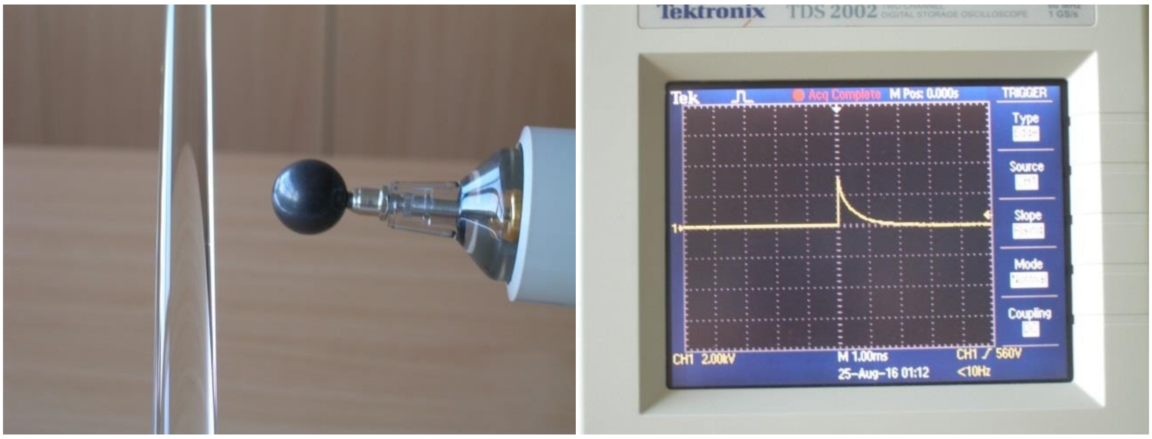

Fig. 10. Discharge of the glass rod into a ball attached to the probe tip

The result is similar to the experiment performed with a PVC tube (except for the pulse polarity). The time constant of discharging is equal. The amplitude of the pulse is affected by different geometric dimensions and material of the rod.

An important fact is that for both glass and PVC rod (regardless of the polarity of the rod charge), the experiment takes place in the same way in the case of the charge bursting into a sharp tip, as well as in the case of the charge "jumping" to a rounded surface. It tells us something about the mechanism of "charge bursting" or "charge jumping". In the vicinity of the sharp tip of the probe, a large electric field is created when the charged rod approaches, in which the ambient air is ionized, charged particles are generated (charge carriers) and thus a “conductive channel” between the rod and the tip is created. In the case of “smooth surfaces” of a rod and a ball, a sufficiently strong electric field is created between them only when they are at very small distance. The amount of charge transferred at one time by an electric discharge is then greater.

The Mystery of Electroscope Charging

One of the basic experiments in electrostatics is to charge an electroscope with an electrified rod. It seems simple: if we touch the conductor on the top pf an electroscope with a negatively charged PVC rod (this we know from previous experiments), the electroscope is charged with a negative charge. **But is this always true?** Let us perform the following experiment using a demonstration electroscope and a PVC tube (hereinafter only abbreviated as rod):

Remove all charged bodies from the electroscope and make sure that it is discharged (shows zero deflection). Ground the metal casing of the electroscope using a suitable connecting wires (for example on the male grounding pin of a socket or a metal component of a radiator). In this part of the experiment, it is not necessary for the electroscope to stand on an insulating pad.

First of all, we just move the electrified rod from above closely to the top of the electroscope. We observe an increase in the deflection of the electroscope leaves. We are not yet touching the top with the rod, we will bring the rod closer only so that the charge does not “jump” onto the electroscope (we don’t hear or see the spark). If we move the rod far enough, the electroscope shows zero deflection once again.

We explain this behaviour standardly by the so-called electrostatic induction, when a negatively charged rod causes a transfer of part of the free electrons (negative charge) in the internal metal components of the electroscope to its lower parts. The top will then remain positively charged, the leaves and fixed lower part will be both charged with a negative charge. As a result of same charge polarities, the leaves and the fixed part are repelled – electroscope shows a deviation. After moving the rod away, the cause for such displacement of electrons ceases, the electrons will return back, parts of the electroscope will no longer be charged and the deflection disappears.

Now we touch (or wipe) the electroscope top with the charged PVC. Just before touching, we will probably register a small electric discharge between the rod and the top. Then move the rod to a sufficient distance. The electroscope will now show a non-zero deflection even after the rod is moved away. Even in relation to the previous paragraphs of this article, we expect that there has been “bursting (or transmitting in a contacts) of a charge” from a section of the rod to the electroscope and thus the electroscope is charged with the same charge as the rod. This charge is distributed over the top, the leaves and all the internal parts of the electroscope and causes the electroscope to deflect due to the repulsion of the moving parts.

We will continue in the experiment. To investigate the sign of the charge the electroscope is now charged with, we use the PVC rod again. We charge it again by rubbing it with flannel or synthetic buckskin and then slowly move it closer to the electroscope top (as we have done in the first experiment from the beginning of this paragraph). Negatively charged rod should cause – due to electrostatic induction we have already described – a shift of free electrons to the lower part of the electroscope, an increase in negative charge in the lower part and thus increase in deviation of the electroscope.

However, with the equipment we used (see Fig. 2), we usually achieve the opposite; when drawing near with the charged rod, in the beginning, the **deflection of the electroscope decreases**. Approaching further it even drops to zero and only moving the rod even closer, the deviation starts to increase. It means that when charging the electroscope with negatively charged rod, the electroscope was charged with a **positive charge, opposite than the charge of the rod**.

When approaching with the negatively charged rod, free electrons shift to the lower parts of the electroscope due to electrostatic induction and the initially positive charge at the bottom is decreased, the result of which is the decreased deflection. As the rod approaches the top of the electroscope, the positive charge at the bottom from the original charge of the electroscope equalizes with the negative charge shifted by induction, and the deflection of the electroscope drops to zero. With the rod even closer these negative charges may even "exceed" the positive charge of the original charge of the electroscope, the lower part is negatively charged and deflection again increases.

How is it possible, though, that electroscope charged with a negatively charged rod is charged with a positive charge? The answer can be found using a high-voltage probe and an oscilloscope. Now we place the electroscope on an insulating pad (foam polystyrene), and connect its casing (that was originally earthed) to a HV probe with a wire (in fact, we earth the casing through a 100 MΩ resistor, which is a probe with an oscilloscope).

Slowly bring the charged rod closer to the electroscope top. At first, the oscilloscope does not detect any change (however, with fast movements of the rod and "more sensitive range" selected on the oscilloscope, a trace movement caused by a charge shifted by electrostatic induction can be observed).

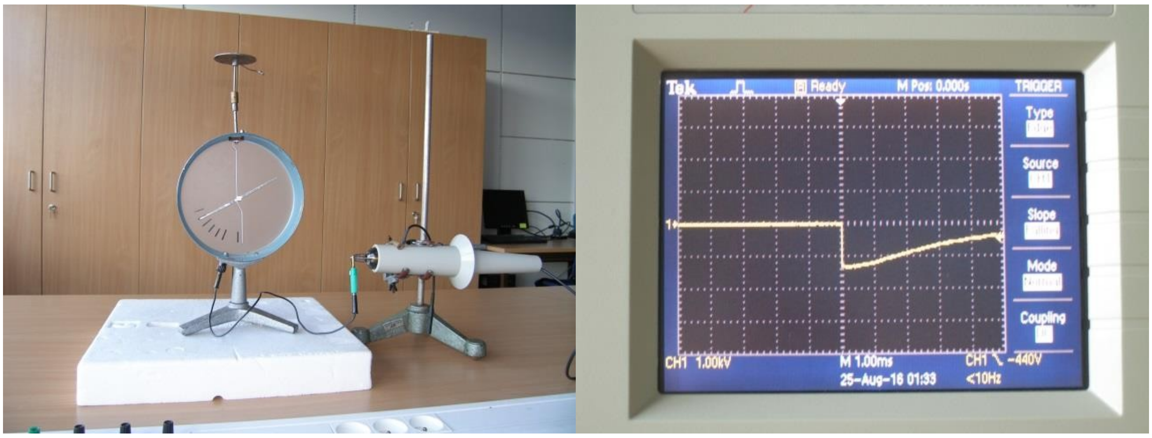

Fig. 11. Charge "jump" into the metal box of the electroscope

At a certain distance of the charged rod from the electroscope top, the oscilloscope registers a negative impulse – negative charge moved through the metal casing of electroscope over the probe into the earth. The only way a charge could get to the metal casing is from the inside by “jumping” from the leaf and inner parts of the electroscope.

The probable cause of the positive charge of the electroscope thus lies in the fact that when the PVC rod gets closer, in consequence of electrostatic induction the lower parts of electroscope are charged so much, that the negative charge “jumps” to the metal casing of the electroscope. When we remove the rod with negative charge, this negative charge is “missing” in the inner part of the electroscope and it is therefore charged positively. The “strength” of the electrostatic induction is influenced by a large part of the surface of the charged rod. Only a small part of the negative charge that “jumped” into the metal casing of the electroscope is then “compensated” when the rod and the top of the electroscope come into contact with each other.

For the conclusion we show an independent experiment on positive charging of the electroscope. We will gradually bring the tip of the probe closer to the metal top of the electroscope until it is discharged.

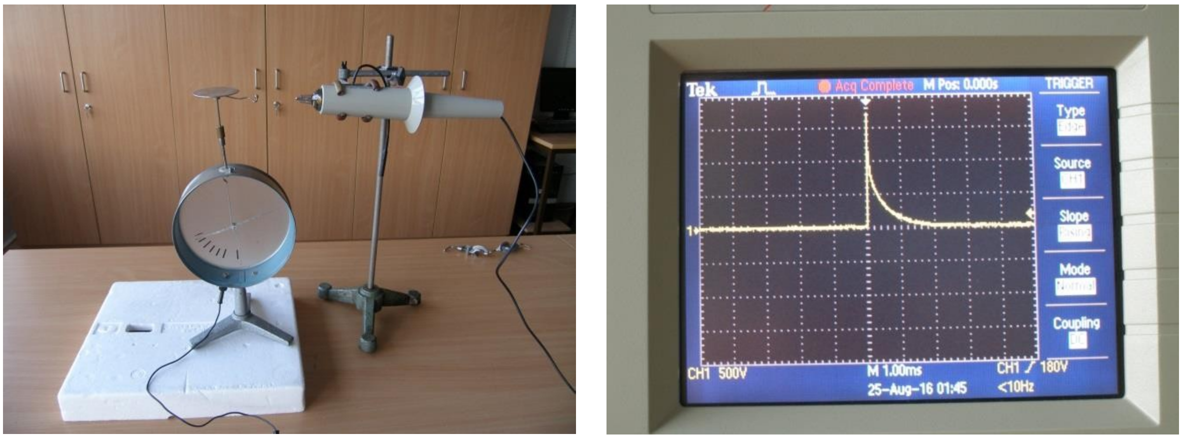

Fig. 12. Charge “jump” from the electroscope top

The oscilloscope registered a positive pulse, so the electroscope was positively charged even when charging with a negatively charged PVC rod.

Conclusion

A digital oscilloscope with a high-voltage probe is a useful tool for understanding the laws of electrostatics. It offers the opportunity to investigate “time dependency” of different charging processes and allows detailed local examination of the charge on the surface areas of insulating materials (e.g. charged rod or a belt from Van de Graaff generator).

When charging the electroscope with an electrified rod, the dominant charging process does not have to be only the transfer (discharge, contact) of the charge from the rod. If we want to express a statement about the sign of the charge by which the electroscope is charged, we have to make an additional experiment with another approaching the rod to the already charged electroscope. If the deflection of the electroscope increases **from beginning** when the rod draws nearer to it, then the sign of the charge of the electroscope is the same as the sign of the charge rod.

A negatively charged PVC rod can often be used to charge the electroscope positively (due to electrostatic induction and the associated charge build-up from the electroscope leaves).

Acknowledgement

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Literature

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[2] Žilavý, P. Alternating currents, ČEZ a. s. in cooperation with P3K, 2012, second edition, ISBN 978-80-87186-65-7.

The mentioned literature is available on the author's website.