WHAT IS THE WORKING PRINCIPLE OF EINSTEIN'S "MASCHINCHEN"?

Danny Segers[1,2] and Jos Uyttenhove[2,1]

[1] Vakgroep Subatomaire en Stralingsfysica, universiteit Gent, Proeftuinstraat 86, B-9000 Gent
[2] Museum voor de Geschiedenis van de Wetenschappen, Universiteit Gent, Krijgslaan 281 (S30), B-9000 Gent

Abstract: *On the occasion of the "World Year of Physics 2005" a lot of expositions around Einstein and his pioneering work in the wonder year 1905 are organised all over the world. Sometimes, the practical realisations to which Einstein contributed receive a lot of attention. One of such instruments to which he contributed was the so called "Maschinchen". The intention was to measure small electrical potentials with this instrument. When the "Maschinchen" is shown in an exhibition not very much is seen: it is a black cylinder with some connectors mounted on it and a coupling for an external motor is provided. What are the physical principles on which the instrument is based?*

1. Introduction

Albert Einstein is known by the general public as a theoretical physicist who changed with his pioneering work in 1905 the general concepts of physics. Of all the theoretical work of Einstein, the formula which is generally known is the one which follows from the special theory of relativity and which expresses the equivalence of mass and energy, i.e.: $E = mc^2$.

It is known that Einstein tried to understand the physical world by "thought experiments". By using pencil and paper he often came to far-reaching conclusions. His special theory of relativity is to a large extend developed in such a way.

What is not generally known about this scientist is that he often contributed to the development of practical realisations. Maybe this is not so surprising. Hermann Einstein (Albert's father) had together with his brother Jacob Einstein a factory for the construction of electrical instruments. It is normal that the young Albert Einstein often walked around in that factory and that he helped with some practical realisations. It is also known [1] that Einstein, as a last year student in the secondary school in Aarau in 1896, obtained much better study results as soon as the new modern physics practical laboratory was installed. Also during his studies at the "Polytechnicum" in Zürich he was very much interested in performing experiments in the physics laboratory of Prof. H. Weber. Later on when he worked as a technical expert at the patent office in Bern (1902 - 1909) he analysed daily technical patent applications. Maybe one can reasonably assume that Einstein was not the one to tackle practical problems with a screwdriver or other mechanical devices, but he certainly possessed a profound physical insight in practical problems.

One of the basic articles Einstein published in 1905 treated the theory of the Brownian motion [2]. This study and also his later work about Brownian motion form the basis of a new field in physics, namely the study of fluctuations. From the methods he developed in the course of this research the modern statistical physics emerged.

In 1907 Einstein tried to contribute to the experimental study of fluctuation phenomena. His prediction of voltage fluctuations in capacitors [3] forms the basis for the development of a new method to measure small quantities of charge (and as a consequence small electrical potentials). Voltages of the order of 0,0005 V (see page 572 in reference [3]) had to be measured. This was not possible with the experimental means available at that time.

To realize a more sensitive instrument, Einstein contacted on the 15th of July 1907 his friends, the brothers Conrad and Paul Habicht. Conrad Habicht had studied mathematics at the “Polytechnicum” in Zürich. Paul Habicht was engineer and active as an instrument maker. He explained to them the new method to measure small quantities of electrical charge [4]. In August 1907 the brothers Habicht had built a prototype of the instrument based on Einstein’s proposed method. This instrument was baptized by Einstein as the “Maschinchen”. At the end of 1907 Einstein dropped the idea of obtaining a patent for this device. Instead in 1908 he described the measuring method in an article in the “Physikalische Zeitschrift” [5]. This paper stimulated further development of the instrument.

The method Einstein described in reference [5] essentially consisted in amplifying a very low initial potential by means of a special electrostatic induction machine (in German: “Elektrostatischer Potentialmultiplicator”), whose output voltage could then be measured with a simple electrometer. That method was not that new [6]: in the first decades of the nineteenth century Giuseppe Belli, a professor in physics at the university in Pavia invented two types of multipliers. His “macchina ad attuazione” (actuating machine) was an induction machine with a rotating glass disk carrying three metallic sectors. The method outlined by Einstein in his paper in 1908 [5] was based on exactly the same principle on which Belli’s machine worked.

2. Einstein’s “Maschinchen” and its working principle

Between 1907 and 1910 Einstein and his collaborators spent much time trying to modify and improve the prototype built in 1907. It took until March 1909 before Einstein seemed ready to begin precision measurements. In November 1909 there were still technical problems to be solved. Finally in March 1910 Einstein and the Habicht brothers tested the machine. In 1910 the device was described by the Habicht brothers in an article in the “Physikalische Zeitschrift” [7]. In December 1911 Paul Habicht demonstrated the machine to the German Physical Society.

Figure 1:
Photograph of the "Maschinchen" of Einstein from the collection of the "Museum Boerhaave" in Leiden (The Netherlands).

For the moment, as far as we know, three devices still exist [9].
One device is available in Wintherhur in Switzerland. In the period 1913 - 1917, Paul Habicht was a lecturer at the "Technicum" in Winterthur. So it is not surprising that such an apparatus was bought there in 1913. It has as inscription: Type 6, No 0035.
A second device still exists in Tübingen in Germany. It was bought by F. Paschen in 1920 (seven years after the purchase of the instrument in Winterthur). Surprisingly, it has a lower number than the Winterthur instrument, i.e. Type 6, No. 0018. It was used by W. Gerlach around 1920 to measure contact potentials in metals [10].
A third apparatus is available in the Boerhaave Museum in Leiden in the Netherlands. It was bought by P. Zeeman around 1912. It is a Type 6, No. 0036. From a study of the scientific work of the Zeeman laboratory, it is not clear for which purpose the instrument was meant. The instrument was donated to the Boerhaave Museum in 1970.

The "Maschinchen" from the Boerhaave collection was shown in the exhibition "Einstein in the low countries" at the "Museum for the History of Sciences" of the University Ghent from 22nd of April 2005 till 2nd of December 2005. Afterwards it will be on view in the permanent collection of the Boerhaave Museum, Leiden. A photograph of Einstein's "Maschinchen" from the collection of the Boerhaave Museum during the exhibition in Ghent is shown in figure 1. Not many details can be seen from the outside. The "Maschinchen" consists of a black cylinder on which a number of connectors are mounted. It is closed with a top plate equipped with some cable connectors. On the bottom a drive mechanism is seen which can be connected to an electromotor with the help of a belt. A central axis can be rotated in that way. On the side connectors an electrometer can be connected as is clearly seen in figure 1.

In figure 2, a vertical and horizontal cross-section through the instrument is schematically shown. This slightly adapted figure is based on the original figures 1 and 2 of reference [7].

In the inside of the instrument six similar sections are mounted on top of each other (section 1 to 6). Each section is electrically shielded from the other sections by a conducting metallic plate (see D in the vertical cross-section). Each section is mounted on four isolated supports (see B in the figure). The supports hold the whole instrument together and three of them can also be seen on the bottom side of the photograph in figure 1. There these supports are mounted on the wooden base plate.

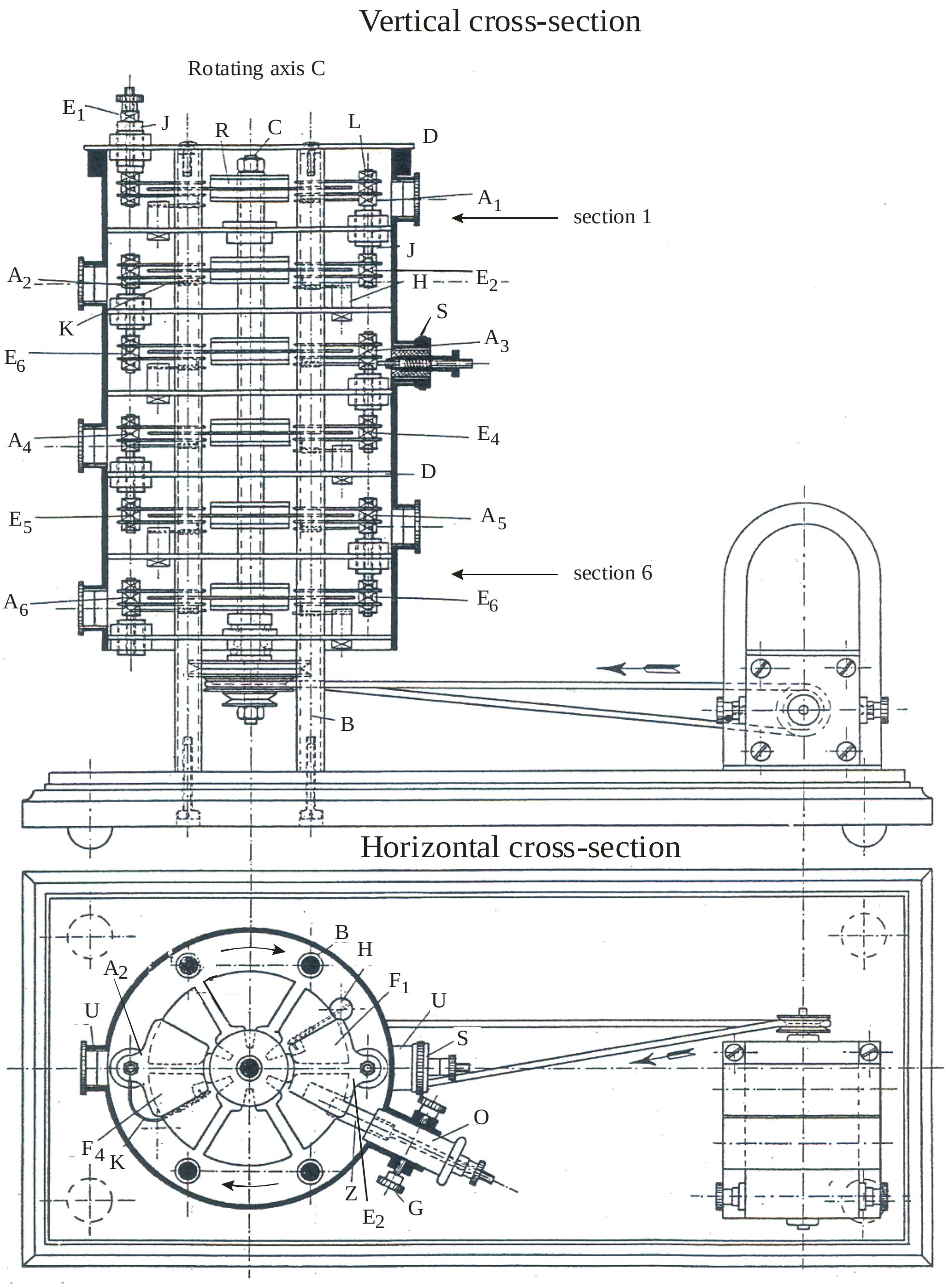

Figure 2:
Schematic representation of a vertical and horizontal cross-section through the “Maschinchen”. It is based on the original figures of reference [7].

On the central axis (indicated by C in the vertical cross-section), six conducting plates (indicated by F_i (i = 1, …6)) are connected. This is clearly seen in the horizontal cross-section of the figure where the plates F_1 and F_4 are indicated. These plates are electrically isolated from the central axis by the isolators R (see the vertical cross-section) and rotate in the instrument. The working principle is that in each section on one side of the instrument, charges are generated on the rotating metal plate by the induction principle. The conductors which generate the induced charges on the rotating metallic plates are called the charge generators (abbreviated by E_1 … E_6 in the vertical cross-section; E comes from the German "Erreger"). These charges are transported by the rotating plates F_i to the opposite side of that section, where by making an electrical contact with the conductor K (see the horizontal cross-section); the induced charge is spread over a conductor. This conductor is called the charge accumulator (abbreviated by A_1 … A_6 in the vertical cross-section; A comes from the German "Abnehmer").

As can be seen in the vertical cross-section in figure 2, the charge generators E_1 … E_6 and the charge accumulators A_1 … A_6 are constructed very symmetrically. The rotating plates F_i are positioned in between two plates of the charge generators or the charge accumulators.

The charge accumulator A_i in section i is electrically connected to the charge generator E_{i+1} in the following section (i+1). This is clearly seen in the vertical cross-section by the following connections: A_1 to E_2, A_2 to E_3, A_3 to E_4, A_4 to E_5 and A_5 to E_6. Since the connecting contact between A_i and E_{i+1} goes through the metallic plate D which shields section i from section (i+1), the connections have to be electrically isolated by the insulators J as seen in the vertical cross-section in the figure.

In the horizontal cross-section of figure 2 a cut through section 2 is shown. The rotating plates F_i rotate there in the clockwise direction as indicated by the arrows in the horizontal cross-section. In the figure it is indicated that just before the rotating plate F_1 enters the space in between the two plates of the charge generator E_2 the rotating plate F_1 is grounded by the springy contact H in the figure. By induction charge separation occurs and due to the grounding springy contact the same charge than the one on the charge generator E_2 is removed from the rotating conductor F_i. When the rotating plate is completely in between the plates of the charge generator, the grounding contact is interrupted. The charge on the rotating plate then reaches its saturation value. This is schematically illustrated in figure 3. The theory can be found in many modern physics textbooks (see f.e. [8])

The induced charge on the plate F_i is then transported to the opposite side of that section to the charge accumulator (A_2 in the horizontal cross-section through section 2). There an electrical contact is made between the rotating plate and the charge accumulator. In the horizontal cross-section in figure 2 the electrical connection is shown by the contact K between the rotating plate F_4 and the accumulator A_2. In that way charge is accumulated on the accumulator A_i until it reaches a steady potential V_i.

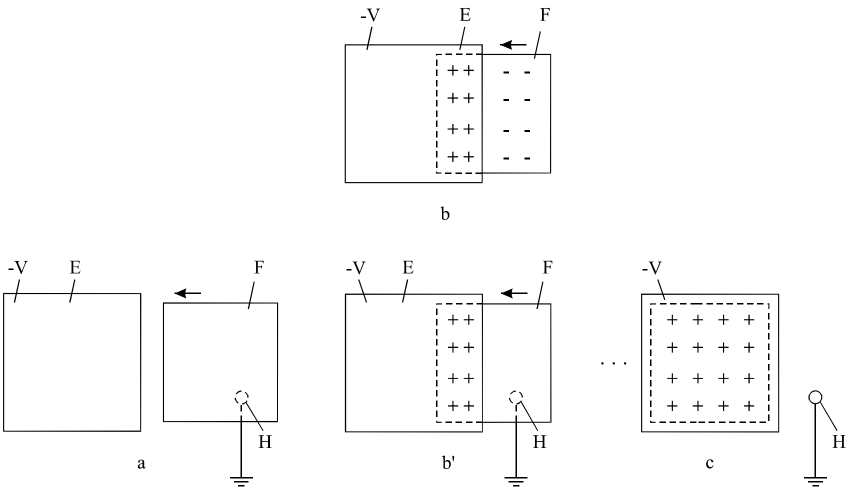

Figure 3:
Schematic representation of the charge generation on the rotating plates.
a) Before the rotating plate F enters the charge generation region E, charges which remained on the plate F, are neutralized by the grounding springy contact H
b) When part of the rotating plate F comes in between the charge generator plates E (which is in the figure on a negative potential -V), charge separation occurs.
b') By grounding the rotating plate, the same charge as the one on the charge generator will be neutralized.
c) When the rotating plate F is completely surrounded by the charge generator E, it is completely charged. This charge will be transported to the opposite side where part of it will be transferred on the charge accumulator.
The arrow on plate F indicates the moving direction.

The potential of the generator E_{i+1} is the same as the potential of the accumulator A_i. The absolute value of the potentials of the different accumulators in the different sections can be written as.

$$\begin{cases} |V_{E_1}| = |V_o| \\ |V_{A_1}| = |V_{E_2}| = |V_1| = a_1 |V|_o \\ |V_{A_2}| = |V_{E_3}| = |V_2| = a_2 |V_1| = a_1 a_2 |V_o| \\ \ldots \\ |V_{A_i}| = |V_{E_{i+1}}| = a_i |V_{i-1}| = a_1 a_2 \ldots a_i |V_o| \\ \ldots \\ |V_{A_6}| = a_6 |V_5| = a_1 a_2 a_3 a_4 a_5 a_6 |V_o| \end{cases}$$

Here a_i is the amplification of stage i. Taken into account only geometrical considerations, it can be shown that a_i is a finite number. In the tests [7] the amplification factor of each stage varied between 8 and 8,8. This led to a total amplification of a factor 360.000. Thus an applied voltage of about 0,0005 V at E_1 (see figure 2) generated a voltage $\left|V_{A_6}\right|$ at A_6 of 100 V. The minimum applied voltage that could be applied to the instrument was estimated to be 5 x 10^{-4} V.

3. The "Maschinchen" was not a success

It has to be noted that the "Maschinchen" was neither a commercial nor a scientific success. The "Maschinchen" is a potential multiplier. Even though the basic theory of the device is quite simple, the construction is complicated. In the instrument moving charged parts cause induced potentials and charge transfer through electrical contacts between different metals cause disturbing induced contact potentials. These inconvenient effects influence the measurements. This was already remarked in 1918 by L. Graetz [11]. In an electrostatic generator (like Belli's "macchina ad attuazione") these phenomena can profitably be used for excitation, but in a multiplier intended for increasing and measuring very weak electric charges these effects are only detrimental.

In the same period other potential measuring devices were drastically improved so that they surpassed the accuracy of the "Maschinchen".

Einstein himself always spoke in a nostalgic way about his little "Maschinchen". In a condolence letter written by Einstein on August 15th 1948 to Conrad Habicht for the death of Paul Habbicht, he wrote: "The memory awakens of old days in which I worked with your brother on the … little machine … It was wonderful, even though nothing useful came of it" [12].

4. Acknowledgements

Dr. G. Veeneman, Dr. M. Fournier and Dr. A. Maas of the Boerhaave Museum are thanked for lending out the "Maschinchen" during the exhibition "Einstein in the low countries" at the "Museum for the History of Sciences" at the university Ghent - Belgium (22/4/2005 - 2/12/2005).

5. References

[1] "The young Einstein, the advent of relativity", Lewis Pyenson, Adam Hilger Ltd, Bristol and Boston (1985) ISBN 0-85274-799-9.

[2] A. Einstein, "Über die von der molekularkinetischen Theorie der Wärme geforderte Beweging von in ruhenden Flüssigkeiten suspendierten Teilchen", Annalen der Physik 17, 549 - 560 (1905).

[3] A. Einstein, "Über die Gültigkeitsgrenze des Satzes vom thermodynamischen Gleichgewicht und über die Möglichkeit einer neuen Bestimming der Elementarquanta", Annalen der Physik 22, 569 - 572 (1907).

[4] "The collected papers of Albert Einstein, volume 2, The Swiss years: writings, 1900 - 1909", Princeton University Press (1989).

[5] A. Einstein, "Eine neue elektrostatische Methode zur Messung kleiner Elektrizitätsmengen", Physikalische Zeitschrift 9, 216 - 217 (1908).

[6] P. Brenni, “Einstein’s ‚Maschinchen’ for the measurement of small quantities of electricity“ in “The collected papers of Einstein, volume 5: The Swiss years: correspondence, 1902 - 1914” Editors: M. J. Klein, A. J. Kox, R. Schulmann; Princeton University Press 1993, p.51 - 55

[7] C. and P. Habicht, „Elektrostatischer Potentialmultiplicator nach A.Einstein“, Physikalische Zeitschrift 11, 532 - 535 (1910).

[8] ”University Physics“ by H. Benson, John Wiley & Sons, inc.

[9] A. Maas, “Het ‚Maschinchen’ van Einstein“, Gewina 27, 159 - 161 (2004).

[10] “Albert Einstein, Ingenieur des Universums, Einsteins Leben und Werk“, Ed. Jürgen Renn, WILEY-VCH verlag GmbH & Co. KgaA. p. 91.

[11] “Handbuch der Elektricität und des Magnetismus“, Band I, by Prof. Dr. L. Graetz, Leipzig, Verlag von Johann Ambrosius Barth, (1918), footnote 1) p.35

[12] “’Subtle is the Lord ...’, The Science and the life of Albert Einstein“ by A. Pais, Oxford University Press 1982, p.485