

Measurement of Ultra-low Ion-Beam Energy

P. Thopan^{1*}, D. Suwannakachorn¹, S. Singkarat^{1,2} and L.D. Yu^{1,2*}

¹Plasma and Beam Physics Research Facility, Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand

²Thailand Center of Excellence in Physics, Commission on Higher Education, 28 Si Ayutthaya Road, Bangkok 10400, Thailand

*Corresponding authors. E-mail: thopan_w@hotmail.com, yuld@fnrf.science.cmu.ac.th

ABSTRACT

Measurement of ion-beam energy is important for assuring equipment operation. When an ion beam is decelerated, its energy becomes very low; the measurement of such low energy is investigated here. Low ion-beam energy has been measured using a retarding field and detector. This research, however, used a deflecting electrostatic field, a simpler and more accurate method. The basic principle of the electrostatic-field application for measuring ion-beam energy is that when an ion beam passes through parallel plates of the electrical field, the beam will be bent from its axial trajectory as a function of the applied field. The bending distance of the ion beam can be used to determine the ion-beam energy. Results of measuring ion-beam energy in this study were compared with theory and simulation results. The SIMION program version 8.0 was used to perform the simulation. A system to measure the ion-beam energy was designed, constructed and installed. The system consisted of a pair of parallel electrode plates, a copper rod measurement piece, a vernier caliper, a stepping motor and a webcam-camera. The entire system was installed under an ion-beam deceleration lens inside the big chamber of the 30-kV bioengineering vertical ion-beam line (CMU3) at Chiang Mai University. The copper rod was moved by the stepping motor to measure the ion-beam current profile, which depended on the beam spot position. The beam profiles were compared between the plates, with and without the electrostatic field, for extracting the ion-beam bending distance and then the ion-beam energy. The ion-beam current, which was on order of 10 nA, was measured by a digital nano-ammeter. Argon ion beams at various energies, ranging from 10 to 20 keV, passed through the deceleration lens resulting in ion energy lower than 1 keV. The measurement results were in good agreement with theoretical and simulated results, demonstrating that the method worked well.

Keywords: Ion-beam energy, Beam current profile, SIMION program, Deceleration lens.

INTRODUCTION

An ion-beam deceleration lens (Thopan et al., 2012) was designed, constructed and installed inside the big chamber of the 30-kV bioengineering vertical ion-beam line (CMU3) at the Plasma and Beam Physics Research Facility, Chiang Mai University. To confirm that the ion beam is indeed decelerated by the deceleration lens according to the design, the ion-beam energy must be experimentally measured.

Low ion energy (< 1 keV) has been measured with various methods (Miyake et al., 1982; O'Connor et al., 1991; Tesmer et al., 1995; Rajput et al., 2010;). For example, the retarding field method (O'Connor et al., 1991) and the repelling plate analyzer (Rajput et al., 2010) used three-ring electrodes placed in front of the detector to measure the function of current drop with voltage given to the electrode. Other methods of measuring ion energy, such as the hemispherical energy analyzer, require more sophisticated instrumentation (O'Connor et al., 1991). A semiconductor detector cannot be used for direct measurement, as the detector's energy resolution is in the same order as the low ion energy to be measured. Moreover, direct ion bombardment may harm the detector. This study developed a simple, cheaper and reliable method by using a deflecting electrostatic field to bend the ion beam and then calculating the beam energy from the bending distance. This paper describes details of the measurement in both principle and device design.

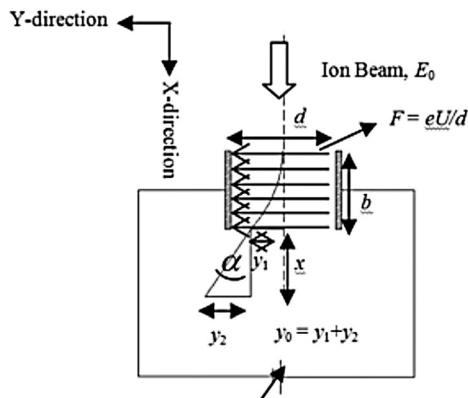


Figure 1. A schematic diagram of the method to measure the ion-beam energy.

THEORY

The basic idea is to use a uniform electrostatic field to deflect the beam, as shown in Figure 1, where the deflection distance depends on the ion energy. As shown in Figure 1, d is the distance between electrode plates, b is the length of plates along with the ion's direction, x is the distance between the end of the plates and the detector, y_1 is the ion bending distance in the uniform field, y_2 is the ion bending distance after exiting the field and y_0 ($y_0 = y_1 + y_2$) is the total bending distance.

When an ion passes through an electrostatic field whose direction is perpendicular to the beam travelling direction, the beam will be bent along a quadratic path. After exiting from the end of the electrostatic field, the beam trajectory is in a straight line. If the electrode plates are too small, the electrostatic field may not be uniform and an edge effect may occur. Thus, to reduce the edge effect, the electrode plates must not be too small. The electrostatic force on an ion passing through the field is:

$$F = eU / d, \tag{1}$$

where e is the unit charge, assuming that the ion is singly charged and U is the voltage applied to the electrical plates. This force deflects the ion's trajectory and accelerates the ion in the perpendicular direction to a final velocity v_h after the ion leaves the field; this does not change the ion velocity v_0 along the incident direction. The total beam bending distance is composed of two parts, one inside and one outside the uniform field.

The first part: an ion passing through an electric field

The first part begins with Newton's second law and eq. (1):

$$\vec{F} = m\vec{a} \Rightarrow eU / d = ma_y, \tag{2}$$

where F is the electrical force on the ion, m is the ion mass and a is the acceleration of the ion in the Y direction (y-axis) perpendicular to the ion incident direction. The time duration of the ion passing the field is:

$$t_1 = b / v_0, \tag{3}$$

where v_0 is the initial ion velocity. The equation of the ion's trajectory is then:

$$y_1 = u_{oy}t_1 + \frac{1}{2}a_yt_1^2, \tag{4}$$

where u_{oy} is the initial velocity in the Y direction, which equals zero. From eq. (2) and eq. (3), the equation of the ion's trajectory (eq. (4)) becomes:

$$y_1 = \frac{1}{2} \left[\frac{eU}{md} \right] \left[\frac{b}{v_0} \right]^2 = \frac{1}{4} \left[\frac{eUb^2}{d} \right] \left[\frac{1}{(1/2)mv_0^2} \right], \tag{5}$$

$$= \frac{1}{4} \frac{eUb^2}{E_0d}$$

where U is in volts and E_0 is the original ion energy in eV.

The second part: the ion's trajectory and the deflecting distance after passing through the electric field

The force that accelerates the ion in the perpendicular direction to the incident direction is:

$$F = m \frac{dv}{dt} \approx m \frac{\Delta v}{\Delta t} = m \frac{v_h}{t_1}. \quad (6)$$

After the ion exits from the electric field, there is a relationship:

$$\tan(\alpha) = \frac{y_2}{x} = \frac{(y_2/t)}{(x/t)} = \frac{v_h}{v_0}. \quad (7)$$

From eq. (3) and eq. (6), there is another relationship:

$$\frac{y_2}{x} = \frac{Ft}{mv_0} = \frac{Fb}{mv_0^2}. \quad (8)$$

Substituting eq. (1) for F in eq. (8) gives:

$$y_2 = \frac{eUbx}{2E_0d}. \quad (9)$$

The total deflecting distance y_0 from the center of the primary ion beam before passing the field is the sum of eq. (5) and eq. (9):

$$y_0 = y_1 + y_2 = \frac{1}{2} \frac{eUb}{E_0d} \left(\frac{b}{2} + x \right). \quad (10)$$

The total beam bending distance depends on the electric field voltage U and the original ion energy E_0 as shown in eq. (11):

$$E_0 = \frac{1}{2} \frac{eUb}{y_0d} \left(\frac{b}{2} + x \right). \quad (11)$$

The measurement error of E_0 can be estimated by the derivative of eq. (11):

$$|\Delta E_0| = \frac{1}{2} \frac{eUb}{d} \left(\frac{b}{2} + x \right) (y_0)^{-2} \Delta y_0. \quad (12)$$

SIMULATION

SIMION program version 8.0 (Manura et al., 2008) was used to calculate the ion-beam bending distance before constructing the device. With known electrical field conditions, including the number, dimensions and configuration of the electrodes of the field, the program calculated the entire electrical field and then the ion trajectory in the field. The simulations were conducted under four conditions and compared with the experimental results. The ion passes through the deceleration lens and then the entrance to the electrostatic field, as shown in Figure 2. The simulation parameters were plate dimensions of $30 \times 30 \text{ mm}^2$,

a thickness of 2 mm ($b = 30$ mm), $x = 40$ mm and $d = 20$ mm. For example, as shown in Figure 3(a), in the first simulation, the original ion-beam energy before entering the deceleration lens was 15 keV. After the ions were decelerated, the ion-beam energy was 230 eV ($E_0 = 230$ eV, as shown in Figure 2). The electrostatic field bent the ions with ion-beam energy of 230 eV. The potentials of the electric plates were 50 V and 0 V, ($U = 50$ V) respectively. The distance of ion bending by the electrostatic field according to theory was 8.9 mm (eq. (10)) and in simulation was 9 mm. In the experiment, we measured the distance of ion-beam bending using eq. (11), and, from the relationship between the distance and the ion energy, we calculated the ion-beam energy. The second, third and fourth simulations are shown in Figures 3 (b), (c) and (d), respectively. The theory and simulation are compared in Table 1.

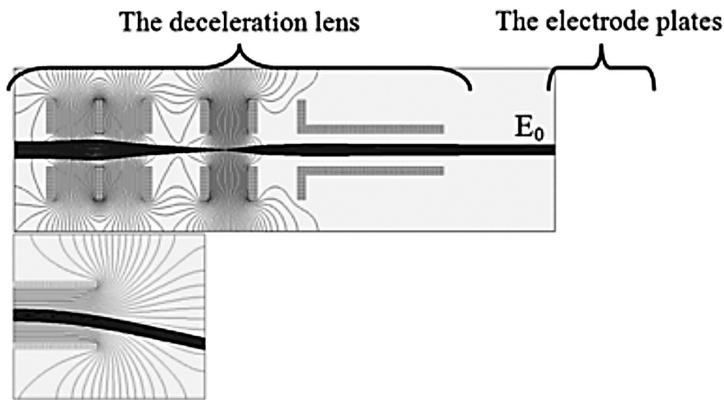


Figure 2. Configuration of the deceleration lens and the electrode plates. An ion travels from the left to right hand side. The red line is the equipotential surface and the blue color is the ion-beam trajectory.

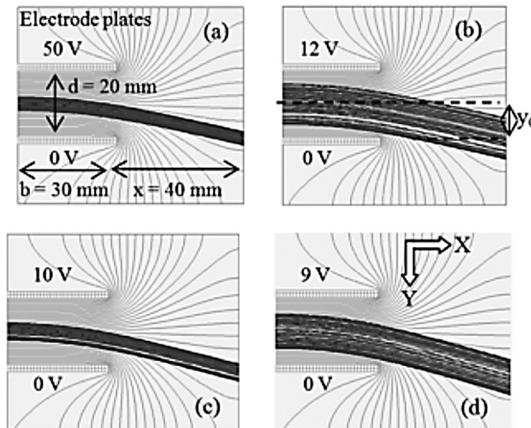


Figure 3. An ion beam bends after passing the electric field, where the bending distance depends on the ion energy. (a) – (d) are the first to fourth simulation, respectively.

Table 1. Summary of the decelerated-ion energy (E_0), electric potential (U), bending distance (y_0) and ion energy error ($|\Delta E_0|$) from theory and simulation, respectively.

	The 1 st simulation	The 2 nd simulation	The 3 rd simulation	The 4 th simulation
E_0 (eV) (Theory)	230.0	56.5	39.0	32.0
E_0 (eV) (Simulation)	230.0	56.5	39.0	32.0
U (V)	50	12	10	9
y_0 (mm) (Theory)	8.9	8.8	10.6	11.6
y_0 (mm) (Simulation)	9.0	9.1	10.4	11.5
$ \Delta E_0 $ (eV) (Theory)	± 26.0	± 6.4	± 3.7	± 2.8
$ \Delta E_0 $ (eV) (Simulation)	± 25.5	± 6.0	± 3.7	± 2.9

MATERIALS AND METHODS

The electrode plates were made from aluminum (2 mm thick (b) and 30 mm in both width and length). The gap between the two plates (d) was 20 mm. The plate edges were covered by a Teflon insulator in order to reduce the edge focusing effect due to a non-uniform electric field at the end of plates. The electrode plates were installed under the deceleration lens (Thopan et al., 2012), which was supported by an acrylic plate of $20 \times 20 \text{ cm}^2$. The deceleration lens system for measuring the ion-beam energy had three parts, as shown in Figure 4. It was installed inside the big chamber of the 30-kV bioengineering vertical ion-beam line (CMU3). The first part was the deceleration lens with a cover and cables. The second part, under the deceleration lens, was the electrostatic plates. The third part was for detecting the ion-beam current. This part consisted of a copper rod on a base, which could be moved by a stepping motor with a diameter of 1 mm and a length of 40 mm. A stepping motor with a controller and a webcam-camera for displaying the copper rod movement were connected to a computer. A vernier caliper for measuring the position of ion-beam bending and a multi-meter were connected to the copper rod to measure the ion-beam current. The distance between the plates and copper rod was 40 mm (x in Figure 1).

In the experiment, the ion-beam current as a function of the position was measured by moving the copper rod. Three conditions were applied: (1) no voltage supplied to the deceleration lens and electrode plates, (2) voltage supplied to the deceleration lens, but not to the electrode plates and (3) voltage supplied to both the deceleration lens and electrical plates. Then, data of the ion-beam current depending on the position were plotted in the Excel program to get three beam profiles, from which we could know the bending distance (y_0) of the ion beam

by comparing the beam profile positions between the plates, with and without supplying voltage. From eq. (11), the ion-beam energy could be finally calculated from the beam bending distance. Argon ion beam was used in the measurement experiment.

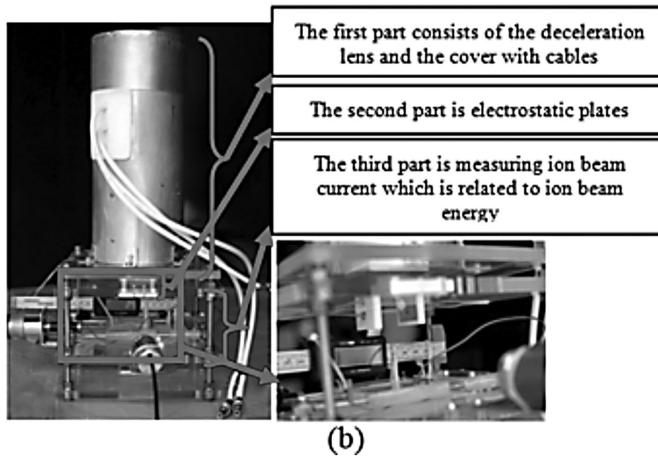
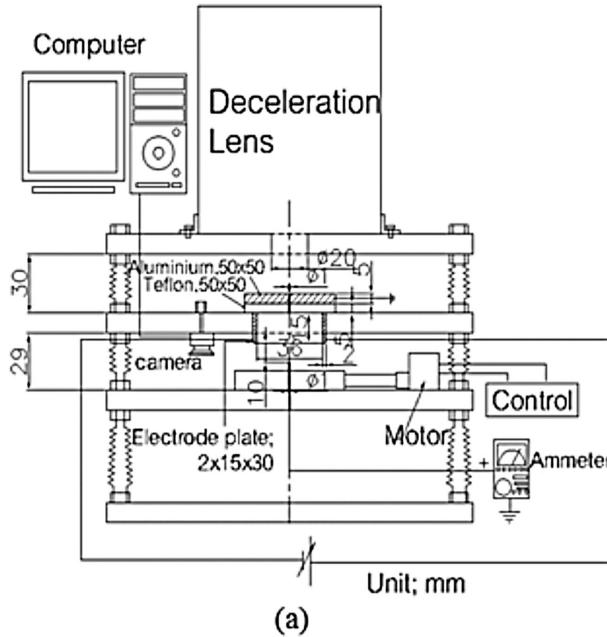


Figure 4. The deceleration lens system for ion-beam energy measurement. (a) Schematic drawing and (b) photograph of deceleration lens system for measuring ion-beam energy. The inset in (b) to the right describes details of each ion energy measurement part.

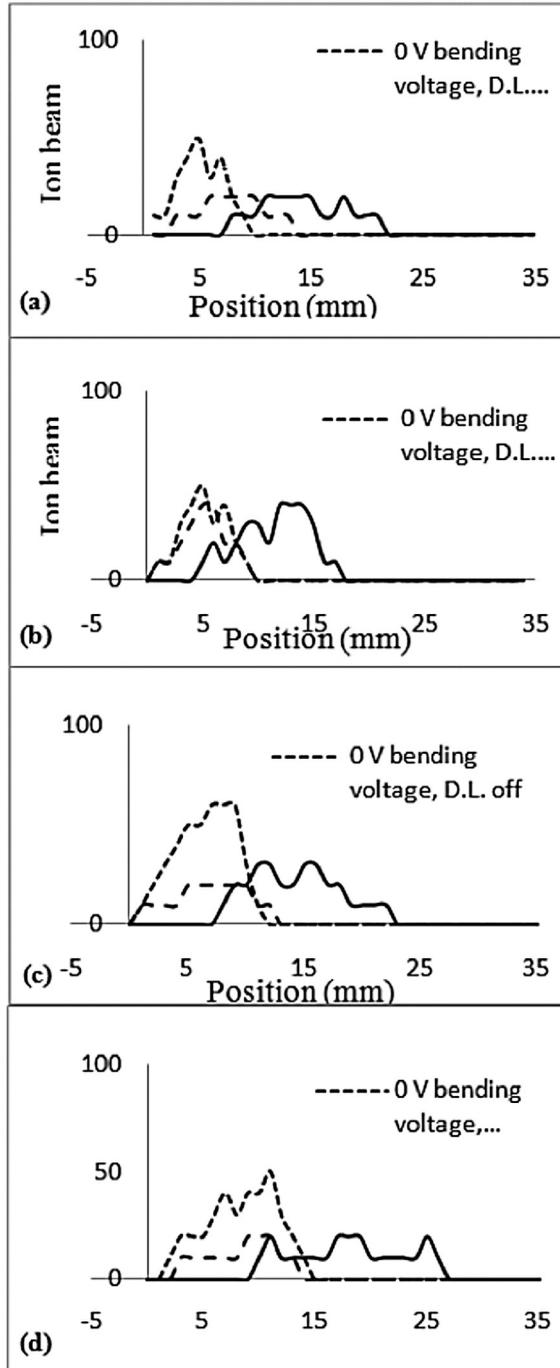


Figure 5. The measured, position-dependent, ion-beam, current profiles. The bending distance of (a) the first experiment is 8 mm, (b) the second experiment is 8 mm, (c) the third experiment is 10 mm and (d) the fourth experiment is 13 mm. From the bending distance, the ion energy could be calculated as shown in Table 2 below.

RESULTS AND DISCUSSION

The measured ion energy is important for confirming the simulation of the deceleration lens by SIMION program version 8.0. The measured ion energy using an electrostatic field to bend the ion beam was related to the ion bending distance by eq. (11) and the measurement error of the ion energy was related to the measurement error in the bending distance by eq. (12). Results are shown in three parts –theoretical, simulated and experimental – under four conditions (see Table 2). The position-dependent, ion-beam currents from the experiment are shown in Figure 5. From the plotted data, we extracted the ion bending distance and finally obtained the ion-beam energy with error by using eq. (11) and eq. (12). The error was calculated based on the measurement copper rod width of 1 mm, i.e. $\Delta y_0 = 1$ mm. As shown in Table 2, the measured ion energy is in good agreement with both the theoretical and program-simulated results, and the errors of the measured ion energy are around 10%. The ion-energy error could occur due to various reasons. One possibility is that the position of the ion beam was not stable at different times due to the limitation of the ion source. A second possibility is that the deceleration lens was not aligned properly and the lens electrodes were not circular, causing ellipticity and astigmatism. A third possibility may be the limitation of the position measurement resolution, based on the copper rod size.

Table 2. Summary of the decelerated-ion energy (E_0), electric potential (U), bending distance (y_0) and ion energy error ($|\Delta E_0|$) from theory, simulation and experiment, respectively.

	The 1 st condition	The 2 nd condition	The 3 rd condition	The 4 th condition
E_0 (eV) (Theory)	230.0	56.5	39.0	32.0
E_0 (eV) (Simulation)	230.0	56.5	39.0	32.0
E_0 (eV) (Experiment)	258.0	62.0	41.0	28.5
U (V)	50	12	10	9
y_0 (mm) (Theory)	8.9	8.8	10.6	11.6
y_0 (mm) (Simulation)	9.0	9.1	10.4	11.5
y_0 (mm) (Experiment)	8	8	10	13
$ \Delta E_0 $ (eV), error (%) (Theory)	$\pm 26.0, \pm 11.3\%$	$\pm 6.4, \pm 11.3\%$	$\pm 3.7, \pm 9.5\%$	$\pm 2.8, \pm 8.9\%$
$ \Delta E_0 $ (eV), error (%) (Simulation)	$\pm 25.5, \pm 11.1\%$	$\pm 6.0, \pm 10.6\%$	$\pm 3.7, \pm 9.5\%$	$\pm 2.9, \pm 9.1\%$
$ \Delta E_0 $ (eV), error (%) (Experiment)	$\pm 32.2, \pm 14\%$	$\pm 7.7, \pm 13.6\%$	$\pm 4.1, \pm 10.5\%$	$\pm 2.2, \pm 6.9\%$

CONCLUSION

The ultra-low energy of a decelerated ion beam was measured using a deflecting electrical field that could bend the beam, a method developed in-house. The bending distance of the ion depended on the ion energy and the electric field strength. The measured ion-beam energy was in good agreement with both theoretical and program-simulated results, within a reasonable error of around 10%.

ACKNOWLEDGMENTS

We wish to thank Dr. Kittikhun Prakrajang for preparing the SIMION program, and Mr. Michael W. Rhodes and Mr. Witsanu Boonsuk for supporting the electronics devices. This study was supported by the Thailand Center of Excellence in Physics (ThEP), the Development and Promotion of Science and Technology Talented Project (DPST) scholarship, the Graduate School of Chiang Mai University and the International Atomic Energy Agency (IAEA).

REFERENCES

- Calsteren, P. V., and J. B. Schwieters. 1995. Performance of a thermal ionization mass spectrometer with a deceleration lens system and post-deceleration detector selection. *Mass spectrometry and Ion Processes* 146/147: 119-129. DOI:10.1016/0168-1176(95)04208-3
- Freeman, J. H., D. G. Beanland, D. J. Chivers, and G. A. Gard. 1978. Ion beam studies part VII: An electrostatic lens for the acceleration and deceleration of high intensity ion beams. *Nuclear instruments and methods.* 155 : 29-37. DOI:10.1016/0029-554X(78)90183-0
- Harasimowicz, J., and C. P. Welsch. 2008. Faraday cup for low-energy, low-intensity beam measurement at the use. The Helmholtz Association of National Research Centers. VH-NG-328 .
- Manura, D. J., and D. A. Dahl. 2008. SIMION® version 8.0 user manual. Ringoes: Scientific Instrument Services, Inc.
- Miyake, K., K. Yagi, and T. Tokuyama. 1982. Direct observation of N₂⁺ ion beam trajectories during deceleration. *Nuclear Instruments and Methods* 198: 535-538.
- O'Connor, P.J., G.E. Leroi, and J. Allison. 1991. Understanding ion deceleration lenses: what are the simplicity/performance trade-offs?. *American Society for Mass Spectrometry* 91: 1044-0305. DOI: 10.1016/1044-0305(91)80024-2
- Rajput, J., A. Roy, D. Kanjilal, R. Ahuja, and C. P. Safvan. 2010. An electrostatic deceleration lens for highly charged ions. *Rev.Sci. Instrum* 81: 043301. DOI: 10.1063/1.3379242
- Tesmer, J.R., and M. Nastasi. 1995. Handbook of modern ion beam materials analysis. Materials Research Society, USA.

Thopan, P., K. Prakrajang, P. Thongkumkoon, and L. D. Yu. 2012. Ultra-low-energy ion bombardment of extracellular DNA using an ion beam deceleration lens, p. 686-692. In Proceeding: 1st ASEAN plus Three Graduate Research Congress.

“Motion in Electric Field” [Online]. (cited 18 March 2013). Available from : <http://www.dlb.sa.edu.au/tsftfmoodle/mod/resource/view.php?>

“Motion of Particle in Electric Fields” [Online]. (cited 18 March 2013). Available <http://www.slideshare.net/cjordison/motion-of-particles-in-electric-fields>

