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Validating the Goldstein–Wehner law for the stratified positive column of dc discharge in an undergraduate laboratory

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Abstract

In this paper we suggest a simple technique for validating the Goldstein–Wehner law for a stratified positive column of dc glow discharge while studying the properties of gas discharges in an undergraduate laboratory. To accomplish this a simple device with a pre-vacuum mechanical pump, dc source and gas pressure gauge is required. Experiments may be performed in nitrogen or even in air. First you need to photograph the discharge tube with striations at different gas pressure values and then you need to determine the thickness of the first striation on a computer monitor.

(Some figures may appear in colour only in the online journal)

Introduction

Stratification of a positive column (successive bright and dark regions) is the most widespread phenomenon in dc glow gas discharge [1]. Striations are observed in many gas discharge devices and they affect their performance. Stratification of the positive column of the dc glow discharge lowers the efficiency of a gas discharge laser. When one performs laser cutting, the presence of striations may lead to defects at the edges of the material under processing [2, 3]. Striations occurring in luminescent lamps lower their efficiency, and the flicker frequency of lamp emissions gives rise to vision fatigue [4]. The presence of striations is also observed in plasma display panels [5, 6]. Therefore, the stratification phenomenon is being studied at many universities by students specializing in plasma physics and plasma technologies.

Standing striations were first observed by Jeremie Joseph Benoit Abria, a little-known French physicist from Bordeaux University in 1843 [7]. They were then studied by many

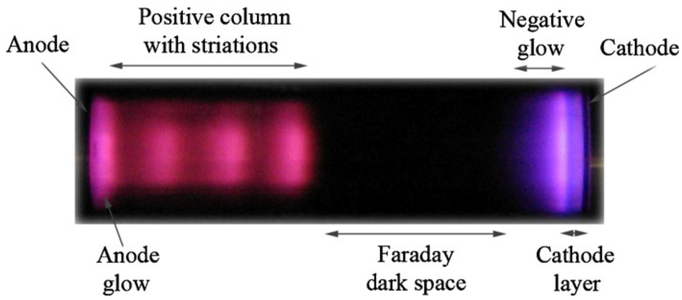

Figure 1. Direct current glow discharge structure with a stratified positive column.

other researchers, and reviews of the work on stratification can be found in [1, 8–11]. Here, for brevity, we will cite only those papers directly related to our problem. Goldstein [12] registered the striation thickness d at different nitrogen pressure values p and revealed the following dependence:

$$d = \frac{f(R)}{p^m} \tag{1}$$

where $f(R)$ is the function of the discharge tube radius R which remained unknown and m is the coefficient less than unity. Wehner [13] performed experiments with a number of gases, employing discharge tubes of different radii in a broad range of pressure values and demonstrated that the stratification process is described by the following formula

$$\frac{d}{R} = \frac{C}{(pR)^m} \tag{2}$$

which is conventionally called the Goldstein–Wehner law. The constant C usually has the order of unity and it depends on the gas species. Thus this law allows one to predict the striation length in discharge tubes of any radius within the pressure range where a stratification of the positive column is possible.

The characteristic pattern of the glow discharge between two electrodes is shown in figure 1. At low pressure the inter-electrode space consists of the following successive dark and bright regions observed visually. Close to the cathode a cathode layer is located consisting of a very *narrow Aston dark space* (it is not discernible in the photo), then there follows a thin layer of the *cathode glow,* and after that there is a dark cathode space also called a *dark Crookes* (or *Hittorf*) *space.* Electric field strength in the cathode layer is higher than in other parts of the discharge, and without the latter a discharge cannot exist. Further from it an abruptly separated region of *negative glow* is located, which becomes evanescent in the anode direction and transforms into the Faraday dark space. After that a *positive column* starts that grows uniformly or possesses a layered structure in the form of layers (*striations*) either standing or moving along the discharge axis. Near the anode a thin sheath of space charge is located, called the anode layer.

Here we are interested in the layered positive column with striations. Within the space occupied by a set of striations the electric field strength, plasma concentration, electron temperature and other parameters vary periodically in space and in the case of moving striations also in time. Each striation consists of a region with a predominant generation of charged particles due to ionization (bright) and a region with a predominant particle loss due to ambipolar escape to the discharge tube walls, attachment to electronegative gas molecules and recombination (dark). Steady (standing) striations are the easiest to observe, and they

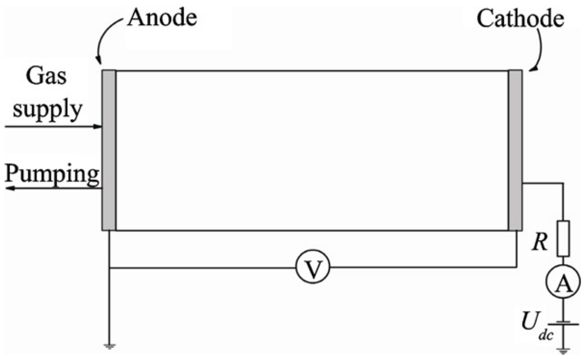

Figure 2. Experimental device setup.

occur in molecular gases (nitrogen, air, hydrogen). In noble gases (helium, argon, neon) one conventionally observes the striations moving with large velocity; a human eye perceives such a positive stratified column as a uniform one, and striations may be revealed only with high-speed optical or probe diagnostics that are not always available in university laboratories. To elucidate the mechanisms of striation formation almost all types of wave and oscillatory instabilities of plasma have been proposed. The main achievement in the study of striations up to the mid-1960s was a definite proof of their ionization-diffusion nature; from this they also became known as ionization waves.

The stratified state at low gas pressure is energetically advantageous, because at the same discharge current the voltage drop and the power dissipated in the positive column with striations are lower than in the uniform one [14]. In bright regions of striations the electric field is stronger than in dark ones and electrons acquire energy required for ionization more easily if you concentrate a sufficient voltage drop across a short section. Electrons lose less energy from collisions with molecules and their acceleration is more effective. Along the dark section of the striation the ionization is small, because the electric field is almost zero or even slightly negative, plasma concentration falls on approaching the anode whereas the discharge current is carried predominantly by the ambipolar diffusion flux. At low gas pressure when the ambipolar escape of charged particles to the tube walls is large it is more advantageous to distribute the potential difference in the form of more or less abrupt jumps with the increased electric field than to extend it along the length of the positive column with a constant gradient.

The aim of the proposed undergraduate laboratory work is to validate the applicability of the Goldstein–Wehner law using conventional photographs of striations taken with a digital camera at different gas pressure values, with simple processing of the obtained images and determination of the striation thickness values.

Experimental conditions for performing the laboratory work

Standing striations are discernible in the direct current discharge in nitrogen as well as in air. Therefore for performing this work one does not need a turbomolecular pump for creating high vacuum as well as containers with very expensive gases. One needs a conventional pre-vacuum mechanical pump.

A sufficiently long discharge tube is also required, which can be made of ordinary glass rather than fused silica glass. The scheme of the experimental device is shown in figure 2. The glass from which the tube is made has to be transparent to provide good striation visibility.

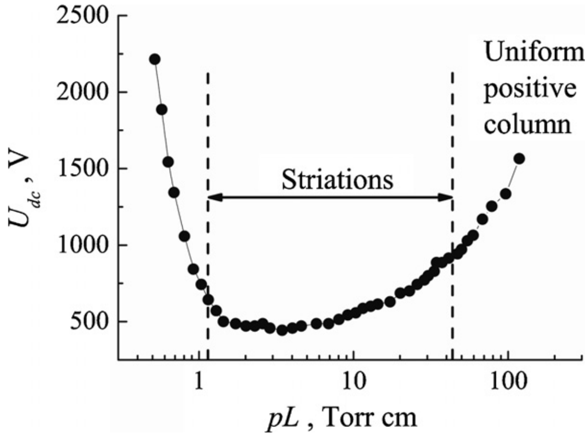

Figure 3. Discharge extinction curve with the existence region of standing striations and uniform positive column. The tube length (inter-electrode distance) is $L = 85$ mm.

The tube length has to exceed seven–eight times its radius to observe several striations. The striations are observed at low pressure (see figure 3), when the total length of the cathode sheath, negative glow and Faraday dark space may attain half (or even more) of the inter-electrode distance; there will therefore be no room for a positive column with striations in a short tube.

Below we present some of our results from studying the stratification process in nitrogen in a discharge tube with an inner diameter of 12 mm and a length of $L = 85$ mm, though striations are observed in a narrow capillary of 3 mm in diameter as well as in a long, wide tube 100 mm in diameter. Figure 3 depicts the discharge extinction curve for this tube as well as presenting the range of nitrogen pressure within which a positive column is stratified. The curve in figure 3 is plotted against the product of gas pressure p and the inter-electrode distance L. As the stratification process obeys similarity laws you may employ figure 3 to predict the pressure range within which you may observe striation in other tubes of different dimensions. Let us assume that in the laboratory a tube of 24 mm in diameter and 170 mm in length is available, which is geometrically similar to our tube but with a radius and length twice as large. Then figure 3 tells us that we can observe striations in this tube within the nitrogen pressure range from 0.07 to 2.5 Torr. Certainly it is not always possible to choose a tube that is similar to ours, but you can at least evaluate the required pressure range for the available tube making use of data presented in figure 3.

The photographs in figure 4 show that with low discharge current the striations shine weakly, but on increasing the current the intensity of their luminosity grows and they are seen more clearly, making determination of their length easier. However, with the current increase the total length of the cathode sheath, negative glow and Faraday dark space grows, while the positive column becomes narrower and the number of striations decreases. With sufficiently large current the positive column with striations disappears completely, and near the anode the anode glow is observed; with further current growth this first becomes dimmer and then it also disappears. The voltage and current values at which the last striation disappears are usually assumed as an upper boundary of the existence region of the stratified positive column for the tube of chosen length. For longer tubes this upper boundary runs higher, i.e. the striations are observed in a broader range of discharge parameters. That is why we recommend employing longer discharge tubes.

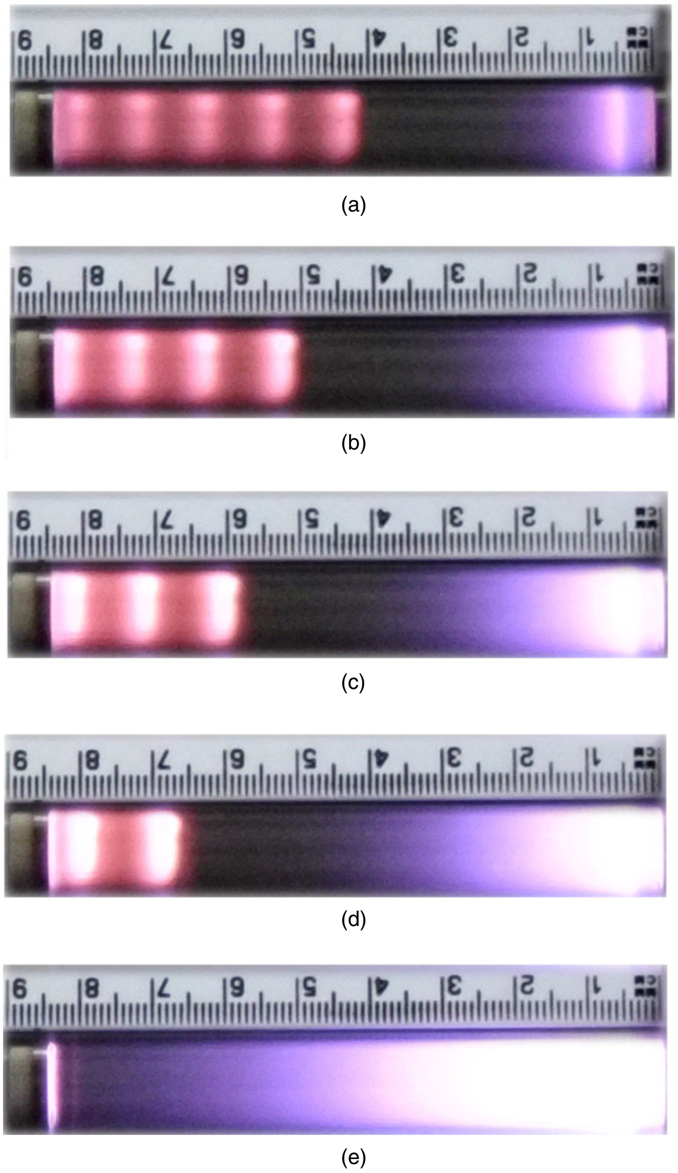

Figure 4. Discharge photograph at the nitrogen pressure of $p = 0.4$ Torr and following discharge current values: (a) 0.5 mA; (b) 1 mA; (c) 1.5 mA; (d) 2 mA; (e) 5.5 mA. Anode is to the left and cathode is to the right.

A direct current generator capable of producing discharge currents up to 100 mA and permitting application of voltage up to 3000 V across the electrodes is required to perform this work. Such high voltage values are required for the gas breakdown in long tubes that follows, e.g., from the results of [15]. Electrodes have to span the total tube cross-section to prevent the ignition of undesirable, parasitic discharges. Before the beginning of the work (one–two days beforehand) the electrodes must be cleansed mechanically of oxide films and other contamination and then also processed in an ultrasound bath with

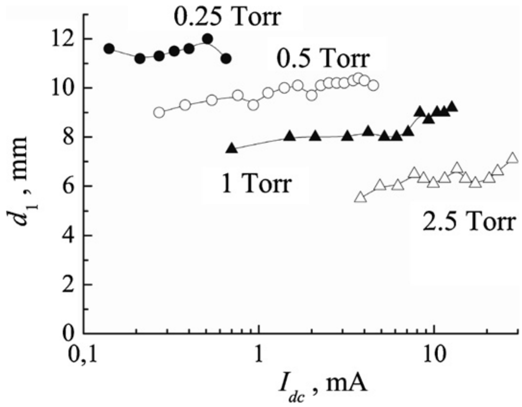

Figure 5. The first striation thickness versus discharge current at different nitrogen pressure values.

alcohol. After that the electrodes are placed inside the discharge tube and they must be kept there in vacuum until the work to prevent oxidization of their surfaces. If the process of electrode cleaning is not performed, then the discharge after ignition becomes unstable and micro breakdowns of oxide films on the electrode surface may occur, accompanied by abrupt jumps of inter-electrode voltage and current, chaotic displacement of striations and a complete positive column.

We also need a voltmeter and an ammeter, which play an auxiliary role and help to evaluate the situation in a discharge tube. Experimental device also has to comprise a gas supply system and a pressure meter (e.g., MKS Baratron 10 Torr or a similar device). In the circuit between the dc generator and the cathode (or anode) a load resistor $R \approx 10$–100 kΩ is included, which limits the discharge current and prevents the appearance of undesirable cathode spots. We also need a digital camera on a support to take high-quality photographs of the burning discharge.

Performing the work

First, students have to acquaint themselves with the stated problem, the experimental device and the registering apparatus required. Then they switch on the device and pump out the discharge chamber to the limiting vacuum which may be attained with the available pump. After that they feed the gas under study (nitrogen or air) to a pressure value a little less than the left boundary of the striation existence range shown in figure 3. After that the pressure is changed with a vacuum valve varying the pumping rate with a constant rate of gas feed (of course, you may employ other options). Under such a method of pressure control the consumption of the gas under study is minimal, limiting laboratory costs.

We fix a white dielectric ruler above the discharge tube with a well-visible millimetre scale for measuring the striation length. The discharge with striations has to be photographed with a digital camera located at a sufficient distance from the tube; e.g., in our case the distance was 2 m.

The striation thickness depends weakly on the discharged current value at fixed gas pressure (what can be seen in figure 5). Therefore students have to take photographs of striations for, say, 7–10 gas pressure values within the range where striations are observed,

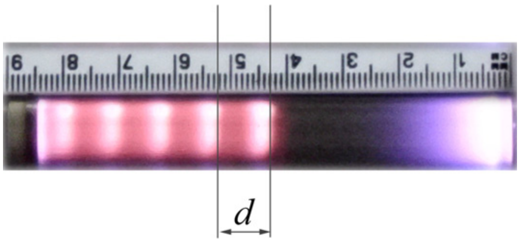

Figure 6. Discharge photograph at the nitrogen pressure of $p = 0.6$ Torr and the discharge current of 1.6 mA. Anode is to the left and cathode is to the right, d is the first striation thickness.

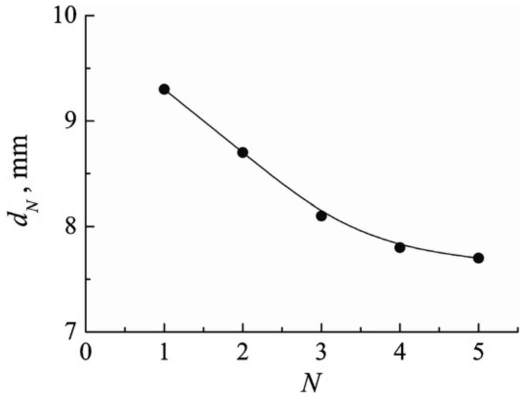

Figure 7. Striation thickness versus its serial number. Nitrogen pressure is $p = 0.6$ Torr, discharge current is 1.6 mA.

taking several shots for different discharge current values for every given pressure value. Then they have to average the striation thickness for every pressure value.

The images obtained are downloaded to a computer. To process them, any program capable of separating a rectangular region (e.g. Adobe Photoshop, MBizGroup PhotoEditor) can be used. The images have to be rotated if the discharge tube is located at some small angle rather than horizontally. Figure 6 depicts the photograph from which you can see how to determine the first striation thickness. From this it can be seen that it amounts to about 9.3 mm. In the same way you can determine the thickness values for the second striation, etc, which is usually a little thinner and dimmer than the first (see figure 7), but in this work they are not important. This is because near the boundaries of the pressure range you can observe one–two striations and further away the positive column glow becomes uniform; it is therefore expedient to deal only with the first striation, which is the brightest one, and is also long and exists in the broadest range of gas pressures.

Each photograph obtained is processed according to the following technique. The thickness values of the first striation measured for different discharge current values at the same gas pressure are averaged and a single average value of the first striation $\langle d_1 \rangle$ is found. This procedure is repeated for other gas pressure values. Then one finds the dimensionless thickness of the first striation $\langle d_1 \rangle / R$, i.e. the obtained values of the thickness of the first striations (in mm) are divided by the tube radius (also in mm). In turn, the values of the gas pressure at which the images were taken are multiplied by the tube radius, but now in

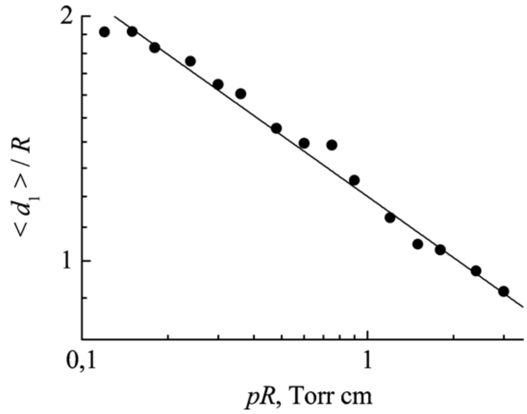

Figure 8. Ratio of the average thickness of the first striation to the tube radius against the product of the nitrogen pressure and tube radius.

centimetres. The dependence $\langle d_1\rangle/R = f(pR)$ obtained in this way is plotted in figure 8 to the logarithmic scale. One sees from the figure that dimensionless thickness values of the first striations match a single straight line (take into account that the scale is logarithmic), which indicates the power dependence of $\langle d_1\rangle/R$ on the product pR. Therefore the Goldstein–Wehner law (3) furnishes a good description of the stratification process of the dc glow discharge and the values of constants from the law (3) for nitrogen are found to equal $C = 1.2$, $m = 0.32$.

Conclusion

We suggest in this paper a simple technique for validating the Goldstein–Wehner law for the stratification of the positive column direct current discharge, employing a simple experimental device within the framework of student laboratory work. To perform this work one is required to take photographs of the discharge tube with striations at different gas pressure values with a digital camera and then to determine the first striation thickness employing a computer monitor.

If one seeks to improve the experimental device described it is possible to add a webcam and a data acquisition system. An average low-cost webcam provides clear enough pictures to analyse and a multichannel data acquisition system will provide an experimenter with a more convenient way of measuring and mapping the electric parameters of the device.

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