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The Use of DC Glow Discharges as Undergraduate Educational Tools

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Abstract

Plasmas have a beguiling way of getting students excited and interested in physics. We argue that plasmas can and should be incorporated into the undergraduate curriculum as both demonstrations and advanced investigations of electromagnetism and quantum effects. Our device, based on a direct current (DC) glow discharge tube, allows for a number of experiments into topics such as electrical breakdown, spectroscopy, magnetism, and electron temperature.

I. INTRODUCTION

Fascinating emergent phenomena arise from the interplay of quantum mechanics and electromagnetism in a plasma. Such complexity encourages scientific curiosity and creative problem solving in the laboratory environment. In fact, much can be learned from the most readily available plasma device: a fluorescent light bulb. Some light bulbs are sold with the coating applied to only half of the tube, enabling the observer to peer into the mercury plasma on the other side. In this way, the plasma can be observed with a spectrometer or manipulated with magnets.[1] The fluorescent light bulb also enables student investigations into plasma ionization and non-linearity by varying the DC voltage powering the light bulb.

A host of more complex investigations can be performed with inexpensive plasma devices. For instance, the spectrum of a sodium discharge tube in a magnetic field exhibits fine-structure splitting due to the magnetic symmetry-breaking found in the Zeeman effect.[2] The set up of such an investigation is simple, but one must consider the response and resolution of the spectrometer to achieve good results (see Section III C). Similarly, one can thoroughly investigate the current characteristics of a plasma using a Langmuir probe which is quite easy to devise, but the interpretation of the data requires an understanding of the delicate interaction between the plasma and the probe (see Sec. III E and Ref. 3). In working with plasmas, students are also introduced to useful laboratory techniques such as vacuum systems, high voltage electrical systems, and data acquisition. Thus, a laboratory device based on plasmas can be quite versatile in that it can be used to demonstrate basic concepts, but also be used for semester-long projects.

In spite of this versatility, the use of plasmas in the undergraduate curriculum is mostly limited to institutions with significant plasma physics research programs or graduate schools. Some authors attempt to remedy this by describing inexpensive plasma devices such an an open flame[4] or inexpensive cathode tubes.[5] Others focus on building a complete suite of experiments[6] or inexpensive fusion research facilities[7] to be used in an advanced undergraduate or introductory graduate courses. We hope to marry the two goals with a single apparatus that can be used to teach physics concepts or be used as a research device in an advanced laboratory.

In Section II, we describe an inexpensive laboratory device based on a direct current (DC) glow discharge for use not only in the advanced laboratory or plasma physics course, but also in standard courses on electromagnetism, quantum mechanics, statistical mechanics, and atomic physics. The five experiments described in Section III can all be incorporated into the undergraduate curriculum as either demonstrations of a particular concept or as an junior-level laboratory investigation.

II. DC GLOW APPARATUS

The direct-current (DC) glow discharge is characterized by two conductors separated by some distance and electrical potential inside an evacuated vessel at moderately low pressures (between a few and a hundred Pascals). The electrical potential is high enough (hundreds to thousands of Volts) to breakdown the gas into a plasma. The characteristics of the plasma are controlled by four variables: potential difference and distance between the electrodes as well as the type of gas used and its pressure. For an excellent description of DC glow discharges, see Ref. 8.

In our instruments, we evacuate glass vessels that house stainless steel electrodes. Each has a two-stage direct drive vacuum pump, an inlet valve system, and pressure sensor. The vessels can be filled with any gas (including air) through one fine and one coarse valve. These valves also enable fine control of the gas pressure from 3 to 300 Pa. We use power supplies that provide a potential difference of up to 2,000 V and 20 mA. To limit currents in the discharge, a ballast resistor of 50–100 kΩ is placed in series with the plasma. For historical reasons, we have developed three different devices, described below, but one could easily incorporate all of the design elements into a single glow discharge according to Fig. 1.

The first of our devices employes a borosillicate glass liquid chromatography column as a vacuum vessel. We use a 600-mm long column with a 75-mm inner diameter. This is a good length to visualize the main components of the DC glow and to provide a sufficient variation in electrode separation when performing a plasma breakdown experiment, as shown in Fig. 2(a). The powered electrode, the anode, is fixed in place, while the grounded cathode is on a long shaft that allows the distance between the electrodes to be adjusted from nearly the entire length of the chromatography column.

The next two apparatuses are variations on the design of the first. The second one has two magnets, one permanent and one electromagnet in order to investigate the effect of an external magnetic field of the plasma. It is also considerably larger than the first one with

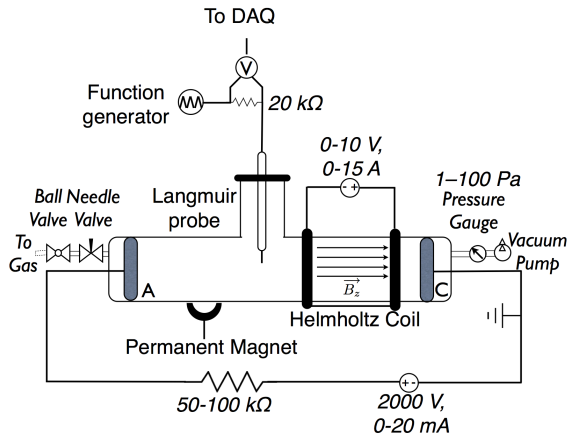

FIG. 1: General schematic of a glow discharge incorporating a movable cathode, a permanent magnet, a Helmholtz coil and Langmuir probe. The DC glow has an anode (A) and a cathode (C) housed in a glass vessel. The electrodes are powered by a high-voltage power supply in series with a ballast resistor. The vacuum system controls the gas pressure via a coarse (ball) and fine (needle) valve that leaks gas in on an inlet port while the vacuum pump removes gas on the outlet port.

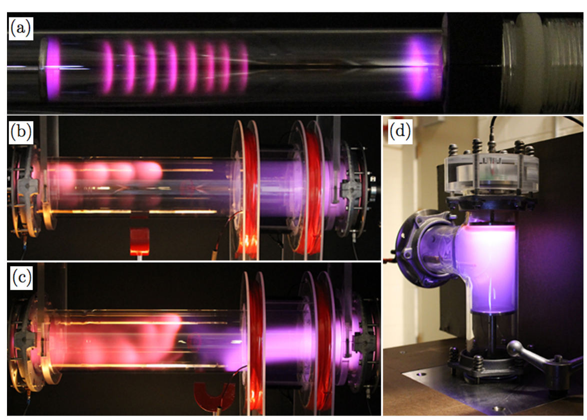

FIG. 2: (Color version online) Three educational plasma devices based on DC glow discharges. The utility of these devices range from the basic (an introductory laboratory device (a)) to the advanced (a DC glow discharge with magnets (b) & (c) and a discharge with Langmuir probes (d)). See the text for more detail.

a length of 1.5 m and a diameter of 15 cm, and therefore, uses electrodes fixed to the ends of the glass vessel (see Fig. 2(b) and 2(c)). The electromagnet is a Helmholtz coil designed to have a 0.027 T magnetic field strength, using 200 turns of wire on each coil and driving it with up to 20 A. This device also incorporates a permanent magnet that translates along the tube length in order to easily visualize the response of the plasma to an external field.

The third device is a glass tee, that allows the addition of a movable tungsten wire into the plasma. The wire acts as a probe, commonly called a Langmuir probe, for measuring currents and potentials in the plasma, and is visible in Fig. 2(d). It also improves on the robustness of the first device by using a linear motion vacuum feedthrough that allows continual adjustment of the electrode spacing without compromising the vacuum integrity.

Note that the placement of the magnetic field coils with respect to the Langmuir probe can be modified depending on one's purpose. The setup shown in Figure 1 enables the smooth compression of a homogenous column of plasma, and reflects the experiments described in Section III. Inserting the probe between the two coils instead would enable control over the plasma density local to the probe.

III. EXPERIMENTS

A. Electrical Breakdown of a Gas

To start the DC glow, air, argon, helium, or another gas filling the gap between the electrodes has to become conductive. The voltage applied by the high voltage power supply (Fig. 1) and hence, the electric field in the gap must be high enough to initiate an electrical breakdown in the gap. In such a breakdown experiment, students measure the starting potential needed to initiate a continuous, self-sustained flow of current through the DC glow tube. This simple and engaging experiment exposes students to a complex, multivariate system that is challenging but accessible on an undergraduate level.

A plasma is formed when a small fraction — 10^{-6} to 10^{-4} — of the atoms become ionized. This occurs when free electrons in the gas gain enough energy from the applied electric field to undergo ionizing collisions with the molecules or atoms of the gas. These collisions are statistically rare, but when the field is strong enough, some of the newly freed electrons produce additional ionizations and start a cascade, called a Thompson avalanche, that produces an exponentially increasing numbers of free electrons. During this stage, the current varies intermittently, an effect that can be detected by fast and sensitive current probes (better than 10 ns resolution, micro-Ampere sensitivity). The ionization avalanches alone cannot sustain the glow discharge, a fact that comes as a great surprise to students. A glow discharge can only become self-sustaining when electron losses are balanced by electron gains.

This balance of electron production and electron losses is determined by a number of interactions within the DC glow. The sources of electrons include primary ionization of atoms and molecules in the gas and secondary emission due to the bombardment of the cathode by positive ions. Electrons are lost when they are absorbed by the walls or anode and when they recombine with ions to produce neutral atoms or molecules.

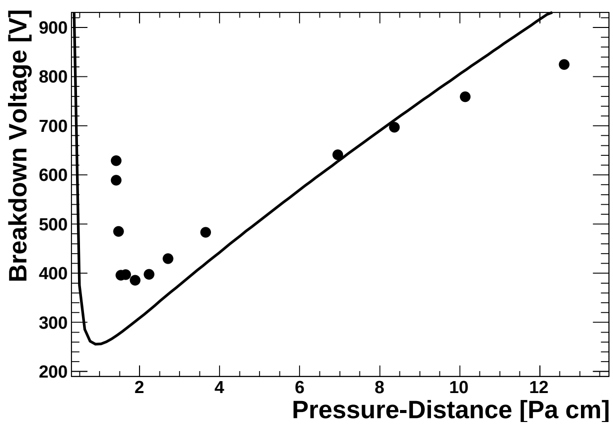

FIG. 3: The voltage at which electrical breakdown begins depends on the pressure of the gas and the distance between the high-voltage electrodes in a non-linear way (circles, experimental data; line, Eqn. 1) with constants for air.

Students can experimentally investigate the dependence of the breakdown or starting voltage on these parameters. Increasing the inter-electrode distance, d, decreases the electric field strength, and decreasing the pressure, P, increases the electron mean free path. Therefore, as students explore the $P-d$ parameter space, it rapidly becomes apparent that the system has a minimum starting voltage that depends on these two variables. DC glows allow students to obtain the classic dependence of the starting voltage on the product of the pressure and inter-electrode distance. The resulting graph, called a Paschen curve, is classically described by Paschen's Law:

$$V = \frac{BPd}{C + \ln(Pd)}. \quad (1)$$

The constants B and C depend on the gas and the probability of secondary electron emission from the cathode, which is a function of the energy of the ions impinging on the cathode and the material used for the electrodes.[9,10]

This investigation invites stimulating questions from students, regarding the shape of the curve, and how well the theoretical curve (the line in Fig. 3) aligns with the data (the circles in Fig. 3). The experimental points are often shifted up above the theoretical curve, as in the figure. In a typical experiment, breakdown voltage is recorded when the plasma begins to glow, but the gas becomes conductive at lower voltages. Error in the measurement of pressure can contribute to a shift in the position of the minimum. Beyond this discussion of experimental error, an interesting classroom discussion can occur when different student groups explore small ranges of pressure and electrode separation, and then have to reconcile their results with each other. Each experimental Paschen curve is different, inviting lively discussions among the students.

B. Electrical Properties of a Glow Discharge

While working on the breakdown experiment, students begin to notice the variations in brightness and color from the cathode to the anode along the axis of the tube. These observations lead to more questions. In fact, DC glow discharges exhibit a fascinating spatial structure, as shown for an air plasma in Figs. 1(b–d). Close to the anode, there is a bright, continuous glow, called the positive column. This is followed by a dark space, and then a bluer, brighter glow—the negative glow—next to the cathode. The striking visual variations in the color and brightness of the light emitted generate a spontaneous flood of student questions. Is there no current (or no plasma) in the dark area? Do the color variations mean different gas species in different areas? What are the mechanisms for the variations in the optical emission energy? Since this is a collision-dominated system, the questions provide an opportunity to examine the nature of collisions and to continue to address conceptual aspects of statistical kinetic theory.

As one lowers the pressure inside the tube, the positive column is broken up into alternating bands of light and dark spaces called striations (see *e.g.* Ref. 11). These bands are caused by the local changes in ionization rate. Increased production of ions causes a region of local positive charge to form slightly behind the corresponding concentration of electrons.

This local field slows the electrons to below the threshold of ionization energy and excitation potentials of the atoms and no light is emitted. As the local electric field is restored closer to the anode, the electrons regain energy from accelerating through the potential and begin to ionize once again and a new bright band appears.

The distance between the bands is related to the electron mean free path and depends on the discharge current, pressure, and the tube dimensions. Striations usually move too fast for visual observations, however, if conditions are just right, standing waves are produced and the bands appear stationary (Figs. 1(a–c)). Students can change the parameters of the system such as pressure, voltage, or the distance between the electrodes and observe their effect on the striations. They can also measure the wavelength of the standing striations, which is roughly $\frac{V}{|E|}$, where V is the ionization potential of the gas and E is the local electric field which can be measured by a Langmuir probe (see *e.g.*, Ref. 3).

After breakdown occurs, current flows freely through the plasma. As such, students can measure the current-voltage relationship for different currents and gas pressures, and determine whether it is Ohmic and compare it to the familiar resistive circuit. Subsequently, the students can calculate the power into the plasma due to resistive losses and compare that to a typical fluorescent bulb or an incandescent bulb.[12] For example, Fig. 4 shows the resistive losses for the plasma at 3.2 Pa can be as low as 0.17 mW. Also we see that the resistance is quite high at low currents. As more neutral gas atoms get ionized, conductivity in the plasma increases, decreasing the resistance.

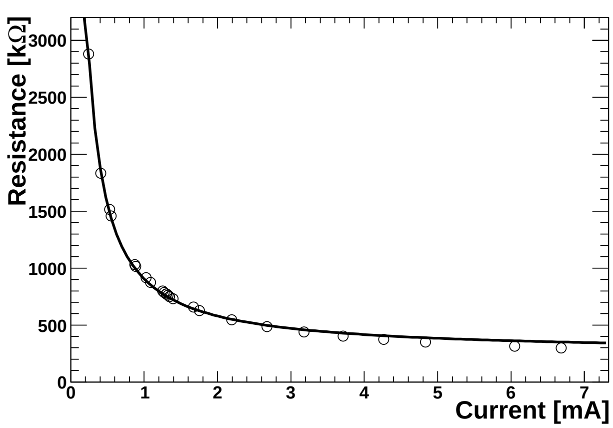

FIG. 4: The relationship between resistance and current for an air plasma at 3.2 Pa (circles, experimental data; line, fit to Ohm's Law).

C. Spectroscopy

Spectroscopy is one of the standard experiments in atomic physics courses. It is also one of the methods of evaluating plasma parameters, such as for example, the electron density and temperature. A simplified analysis of DC glow optical emission is readily accessible to undergraduate students and can add a quantitative component to the discussion of the color variations mentioned previously.

In a DC glow discharge, light is typically emitted by neutral atoms that are excited by electron collisions. This presents a challenge to students: they must identify the possible factors affecting the line intensities observed in an experimental spectrum. Such factors include: excitation probabilities, the mechanisms and the probability of de-excitation, the optical density of the medium, and the response function of the spectrometer. The excitation probabilities also determine the relative number and the energy of the excited levels. One can usually assume that in a DC glow discharge the observed light is emitted in spontaneous transitions, and passes unchanged to the CCD detector of the spectrometer. If we further assume that electrons collide with atoms in ground states, then the distribution of the excited levels depends on the electron energy distribution and collision and excitation probabilities. Experimentally observed line intensities are therefore related to the electron energy. Therefore, the observed intensities can be used to estimate the electron temperature of the plasma, under the assumption that the electrons follow a Maxwell-Boltzmann energy distribution.

The electron temperature can be determined as the reciprocal of the slope of the line when the logarithm $\ln(\lambda_{ik} I_{ik}/(g_k A_{ik}))$ is plotted versus the excited energy level E_k in eV:

$$ln \frac{\lambda_{ik} I}{g_k A_{ik}} = -\frac{E_k}{kT_e} + C, \tag{2}$$

where the wavelengths are given by λ_{ik}, their corresponding observed intensities are I_{ik}, kT_e is the electron temperature in eV, g_k is the quantum degeneracy of the upper level, A_{ik} is the transition probability for spontaneous radiative emission from k to i, and C is a constant.[13] Since E_k is usually much greater than kT_e (about 15 eV or higher versus about 1 eV), the estimate of T_e is improved by choosing lines originating from a upper states with a broad range of energies. In addition, the lines with upper levels excited from metastable levels (common for noble gasses) should be excluded from the analysis since these are dependent on electron density rather than temperature. For example, in argon the 811.43 nm line is metastable.

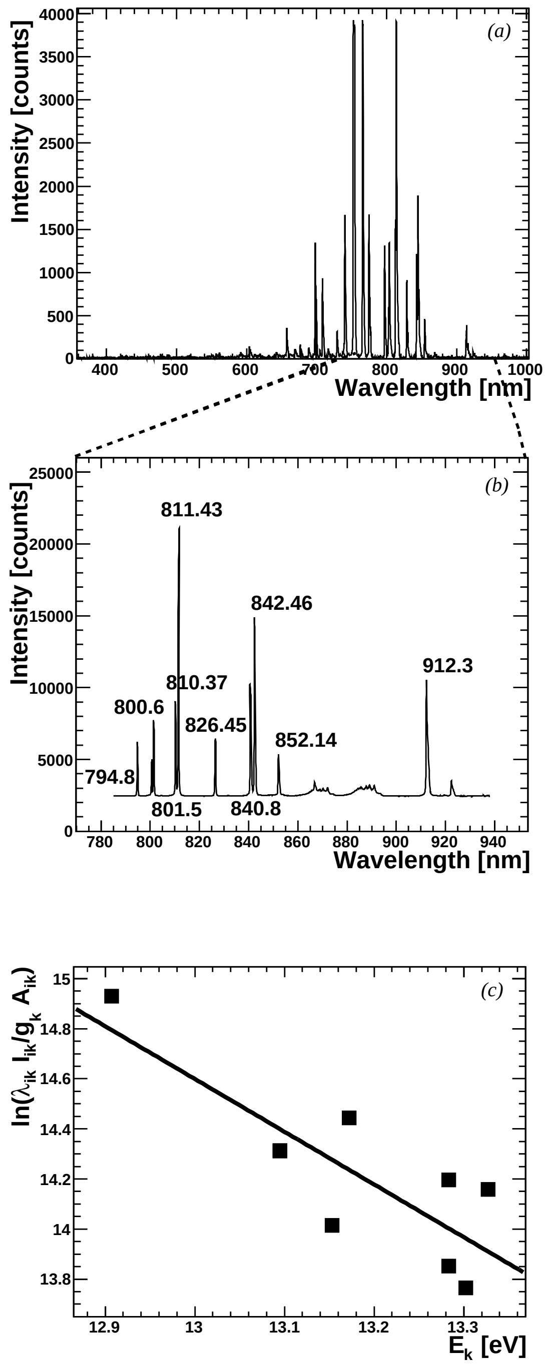

FIG. 5: (a) Survey spectrum of argon (b) High-resolution spectrum of argon taken in the 780–920 nm range yields spectral lines used to construct (c) a Boltzmann plot in the positive column. The linear fit yields an electron temperature of ~ 0.5 eV.

We used an Ocean Optics USB2000 spectrometer for a broad survey spectrum of the positive column of argon in a DC glow discharge, shown in Fig. 5(a), and a QE6500 for a higher resolution spectrum in the 780–920 nm range (Fig. 5(b)). The latter spectrum had a high enough spectral resolution to distinguish individual lines. The lines were used to construct a Boltzmann plot based on Eqn. 2 and shown in Fig. 5(c). The measured line intensities were corrected for variations in the quantum efficiency of the CCD detector. The transition probabilities, A_{ik}, and energy level information were obtained from the NIST Atomic Spectra Database.[14] Using the reciprocal of the slope of the regression line fitted to the data in Fig. 5(c), we estimated the electron temperature in the positive column to be ~ 0.5 eV.

We continued to measure the electron temperature throughout the positive column and the negative glow for pressures between 33 and 66 Pa and currents between 10 and 20 mA. The linearity of the points in each Boltzmann plot is affected by the range of upper level energies for argon lines, which in our case is limited to < 0.4 eV in the 780–920 nm range due to the wavelength range of our spectrometer. The error in this measurement is reduced with a high resolution spectrometer with a broader range. Our estimates show that the electron temperature in the positive column increases slightly from about 0.5 eV to 0.6 eV with increases in pressure and current. The electron temperature is much higher, about 1 eV in the negative glow, where the DC glow appears bluer. These estimates agree with the variations in the color along the length of the tube that students can easily see.

D. Magnetism

Students can learn a great deal from a plasma source by exploring the effects of a magnet on the charged particles within the tube. The ability to "move the light" brings into question all that they know of light, electricity, and magnetism. Furthermore, bringing a magnet near a plasma is among the only ways students can actually visualize the effect of magnetic fields on charged particles.

Running a current through a Helmholtz coil induces a magnetic field along the axis of the tube, due to Ampere's Law. The curvature in the magnetic field outside the Helmholtz coil and the strength and uniformity of the field inside the coil[15] produces a dramatic pinch in the observed light from the plasma. Since the visible electromagnetic emission is from collisions of electrons with neutral air atoms, students can use the plasma to get a rough estimate of the shape of the magnetic field from the coil.

Far from the Helmholtz coils, the magnetic field is zero, but to conserve magnetic flux, the field immediately outside must curve back around the coils. Since the charged electrons experience no force along the field lines, they will tend to gyrate along the field with radial transport across the field lines greatly decreased. Thus, one can observe that the plasma emission also shows no change far from the coil, a strong curvature near the coil, and a significant reduction in the radial dimension, depending upon the strength of the magnetic field (see Fig. 2(c-d)).

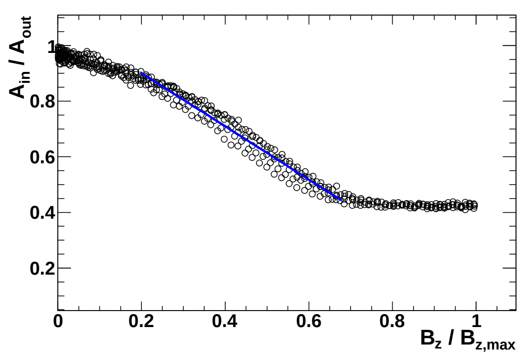

FIG. 6: (Color online) The ratio of visible plasma area interior A_{in} and exterior A_{out} to the Helmholtz coil, as a function of increasing magnetic field shown line a linear fit (blue line). The radius of the plasma in the vertical direction was estimated through a moment analysis that fits each frame to an ellipse (black circles).

Magnetized plasmas are a good demonstration of Alfvén's Theorem, which maintains that magnetic fields are frozen in place in a moving, conducting fluid and that magnetic flux is conserved. Therefore, if the magnetic field through the Helmholtz coils is increased by some factor, the visible area of the plasma should be reduced by the same factor. As shown in Fig. 6, driving the Helmholtz coils with a varying magnetic field induces a pinch. At low magnetic field strength, the plasma extends to the walls of the vacuum vessel, and at high values, the pinch saturates. While a DC glow is not a perfect conductor, a linear fit in the region where $0.2 < B_z/B_{z,max} < 0.65$ indicates that the area fraction decreases with a slope of -0.96 ± 0.01 with increasing magnetic field.

E. Plasma Probes

Plasma probe studies allow students to investigate properties of the DC glow plasma such as the electron and ion temperatures and potentials inherent in the plasma. This offers students a unique opportunity to see how the large mass difference between electrons and ions affects particle mobility, and to gain an understanding of how the potential differs in a DC glow discharge from a parallel-plate capacitor. Additionally, a comparison of probe studies and spectroscopic methods illustrates consequences of measuring techniques that perturb the system they are measuring, and those that do not.

A probe is any conductor inserted into a plasma that collects current. The properties of a plasma can be determined from the measurements of the current on the probe as a function of the bias potential applied to the probe. Such probes directly detect electron and ion flows in the plasma and, at the same time, disturb their surroundings. Any conductive material can act as a plasma probe (wire, foil, walls of the chamber etc.); however, careful control of the size, shape and material of the probe is required to obtain discernible plasma quantities. Probe tips are typically made from refractory metals, such as tungsten, and are housed in robust ceramics such as boron nitride. Probe shapes can be cylindrical, spherical, and planar, and the number of probe tips within a single device vary from one to four. When constructing a Langmuir probe, both shape and size are determined based on estimations of the expected Larmor radius and Debye screening length of the plasma ($\sim 10^{-5}$ cm from Ref. 16).[17] Here, we use the most basic of Langmuir probes, the single cylindrical probe. Ours has a diameter of 0.1 mm and exposed conductor of length of 5 mm.

Although both electrons and ions are charged particles, only the electrons gain a significant amount of energy from the potential field created between the anode and cathode. Elastic collisions of electrons with neutral atoms transfer almost no energy to the neutral atoms. The result is a plasma with electrons at a much higher temperature than the ions and neutral atoms. The electrons therefore have a higher probability of leaving the plasma, leaving it slightly positive with respect to the walls of the chamber. Consequently, the bulk of the plasma reaches a metastable electric potential, called the plasma potential, V_{plasma}. If the probe potential is equal to the plasma potential, the probe does not perturb its surroundings and does not change particle flows. At bias voltages higher than V_{plasma}, the flow of electrons to the probe increases, and the current becomes negative. At voltages lower than V_{plasma}, the current is positive, because the electrons are repelled and the ion flow dominates the current to the probe.

In order to study the potentials in the plasma, we start by inserting an unbiased probe into the bulk of the plasma. A Debye shield forms around the Langmuir probe, thereby lowering the potential local to the probe. Thus, an electrically neutral probe will not record the plasma potential, but a lower value denoted as the floating potential V_{float}, whose difference from V_{plasma} is a function of the electron temperature.[18] The bias voltage is then programmed to sweep the probe through potentials $\sim \pm 20$ V from the floating potential in order to span the region well beyond the expected position of the plasma potential (above V_{float}) and the ion saturation region (below V_{float}).

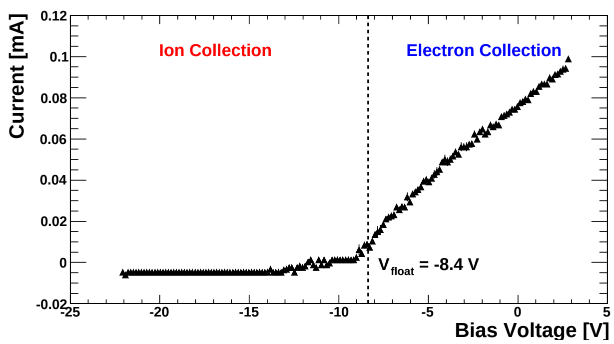

FIG. 7: (Color version online) Data set from the Langmuir probe. Below the floating potential V_{float}, ion current is dominant; above, only electron current is collected.

The current, I, at each bias voltage, V, can be seen in Fig. 7, in which our floating potential was recorded to be -8.4 V. Note, the apparatus used for the Langmuir probe study utilized a negative power supply to power the cathode and the anode was tied to ground. In this way, all voltage measurements are recorded as Volts below ground. Considering the mass of the ions, m_i, and electrons, m_e, the plasma potential can be calculated as (following the treatments in Refs. 3 and 19):

$$V_{plasma} = V_{float} + \frac{kT_e}{2} \ln\left(\frac{2m_i}{\pi m_e}\right). \quad (3)$$

In order to calculate the plasma potential, we need to estimate the electron temperature. As it turns out, we can also use the $I-V$ curve shown in Fig. 7 to measure the electron temperature in the plasma. Just above the floating potential, the current is exponentially increasing. In this region, the average electron temperature depends on the slope of current versus voltage relationship, according to:

$$kT_e = \frac{dV}{d\ln(I)}. \tag{4}$$

Using this method, we find an of electron temperature of 0.75 eV, which agrees to within errors with the results from Section III C. With these measurements, Eqn. 3 yields a plasma potential of -4.7 V.

If we assume a Maxwellian temperature distribution for the electrons and ions, we can calculate their mean velocity as:

$$v_{th} = \sqrt{\frac{8kT_{e,i}}{\pi m_{e,i}}}. \tag{5}$$

Assuming that the ions in our DC glow plasma are predominately nitrogen ions at room temperature of $\sim$ 25 meV, the ion mean velocity is 460 m/s. Using the results above for the electron temperature, the mean velocity of the electrons is 5.6×10^5 m/s. Students will, therefore, see that the electron velocity is three orders of magnitude higher than the ion velocity, comparable to the difference in mass between the ions and electrons.

This method does well to illustrate the velocity difference between the ions and electrons in the system; however, several assumptions were made in order to calculate the electron temperature. While it is a good approximation, the electron velocities do not completely follow a Maxwellian distribution. Furthermore, as the probe bias voltage is increased, the Debye length grows and increases the effective probe surface area. When the Debye length becomes an appreciable fraction of the chamber dimensions, the probe becomes a third electrode for the system, changing the structure of the plasma. This last problem was avoided by limiting current consumption, by using a small probe, and maintaining a bias voltage lower than the anode. The combination of these assumptions and challenges give an uncertainty on the order of the measurement, which makes for a useful discussion with students about experimental uncertainty.

IV. CONCLUSION

The DC glow discharge proves to be an effective teaching tool in physics education. We have described here a series of experimental apparatuses varying in cost and footprint, but designed for ease of use for undergraduate laboratories.

The experiments described here serve as a first-rate introductions to plasmas and complex systems. Students are simultaneously introduced to vacuum systems, simple circuits and high voltage systems. As such, we believe that this basic introduction to the plasma physics is an excellent foray into experimental techniques and the scientific method and perhaps leading to further research in basic plasma physics.

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