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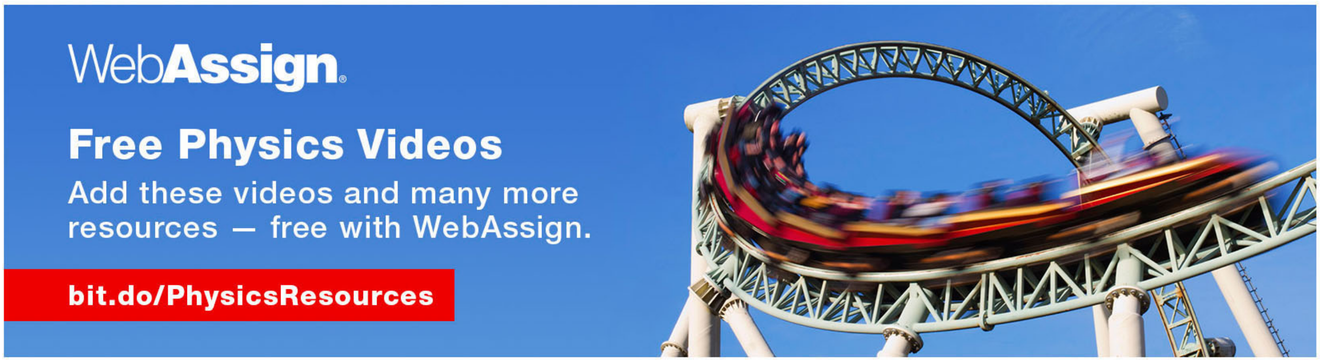

The use of dc glow discharges as undergraduate educational tools

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Plasmas have a beguiling way of getting students 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. We describe a device, based on a direct-current (dc) glow discharge tube, which allows for a number of experiments into topics such as electrical breakdown, spectroscopy, magnetism, and electron temperature. *© 2013 American Association of Physics Teachers.*

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I. INTRODUCTION

Fascinating emergent phenomena arise from the interplay of quantum mechanics and electromagnetism in a plasma. Much can be learned, in fact, 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. The plasma inside can be observed with a spectrometer or manipulated with magnets.[1] Students can also use the fluorescent light bulb to investigate plasma ionization and non-linearity by varying the dc voltage powering the bulb.

A host of more complex, but self-contained investigations can be performed with inexpensive plasma devices. For instance, quantum-mechanical effects such as the Zeeman effect[2] and atomic vibrational states[3] can be investigated with spectral discharge tubes. The setup of such spectroscopy experiments are straightforward, although students must consider the response and resolution of the spectrometer to achieve good results (see Sec. III C). Vacuum tubes can be used to measure not only the charge-to-mass ratio of the electron[4] but also the conductivity of ionized gases.[5] These more complex investigations encourage scientific curiosity and creative problem solving and can act as self-contained experiments that complement lecture-based courses.

A full-scale laboratory device based on plasmas can be used for demonstrations and week-long experiments but can also be used for semester-long projects. For example, one can thoroughly investigate the characteristics of a plasma using a Langmuir probe that is 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 Refs. 6 and 7). In the past, authors have published descriptions of other plasma sources in this journal including an open flame[7] and inexpensive cathode tubes.[4,8] Others focused on building research facilities[9,10] or a complete suite of experiments[11] to be used in an advanced undergraduate or introductory graduate course. We hope to marry these two goals with a single apparatus that can be used to teach basic physics concepts or be used as a research device in an advanced laboratory.

In Sec. II, we describe an inexpensive laboratory device based on a 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 Sec. III can all be incorporated into the undergraduate curriculum as either demonstrations of a particular concept or as junior-level laboratory investigations.

II. DC GLOW APPARATUS

The dc glow discharge is composed of 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 needs to be 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. An excellent description of dc glow discharges can be found in Ref. 12.

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 a 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 2000 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 distinct devices, as described below, but one could easily incorporate all the design elements into a single glow discharge according to Fig. 1.

The first of our devices, shown in Fig. 2(a), employs 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. 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 along nearly the entire length of the chromatography column. All electrical cables are coaxial, properly grounded, and rated for the voltage and current used to protect against the safety hazards inherent in the system.

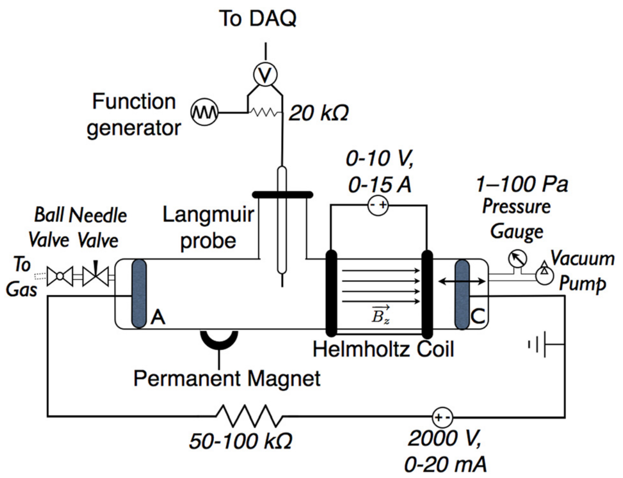

Fig. 1. General schematic of a glow discharge incorporating a movable cathode, a permanent magnet, a Helmholtz coil, and Langmuir probe. The dc glow has an anode (a) and a cathode (c) housed in a glass vessel. The electrodes are powered by a high-voltage power supply in series with a ballast resistor.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

The next two apparatuses are variations on the design of the first. The second one has two magnets, one permanent and one electromagnet, to investigate the effect of an external magnetic field on the plasma. The glass column is also considerably larger than in the first device with a length of 1.5 m and a diameter of 15 cm, and therefore uses electrodes fixed to the ends of the glass vessel. The electromagnet is a Helmholtz coil designed to produce a 0.027-T magnetic field using 200 turns of wire in each coil and driving it with up to 20 A. This device also incorporates a permanent magnet that translates along the tube length to visualize the response of the plasma to an external field [see Figs. 2(b) and 2(c)].

The third device is a glass T 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 [this probe can be seen in Fig. 2(d)]. This device 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.

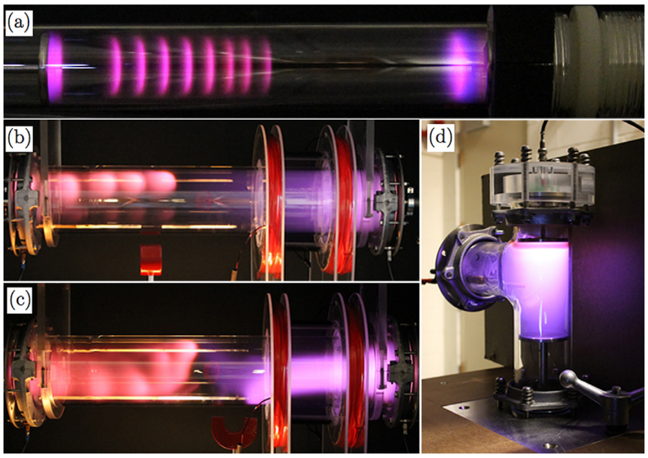

Fig. 2. (Color online) Three educational plasma devices based on dc glow discharges: (a) a basic, introductory laboratory device, (b) and (c) an advanced dc glow discharge with magnets, (d) a discharge with Langmuir probes. See text for more details.

Note that the placement of the magnetic field coils with respect to the Langmuir probe can be modified depending on the purpose. The setup shown in Fig. 1 enables the smooth compression of a homogenous column of plasma, and reflects the experiments described in Sec. III. If instead the two coils surround the probe, one can control the plasma density in the vicinity of 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, must become conductive. The voltage applied by the high voltage power supply and hence the electric field in the gap, must be high enough to initiate 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 at the 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—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, μA 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.

Ionizing cascades multiply the number of electrons in the plasma by a factor of $e^{\alpha d}$, where α is the first Townsend coefficient and d is the distance between the electrodes. Electrons are also emitted from the cathode by a factor proportional to the number of ions at the cathode. The probability that an ion bombarding the cathode will eject electrons is expressed in the second ionization coefficient γ. The discharge becomes self-sustaining if secondary emission replaces each initial electron that starts an avalanche; that is, when $\gamma(e^{\alpha d} - 1) = 1$.

It is empirically found that α depends on d, the pressure p, and the electric field E according to $\alpha = Ape^{-Bp/E}$, where A and B are constants that depend on the particular gas being used. The minimum applied voltage that results in a self-sustaining glow discharge can be determined by combining the two expressions given above. The resulting expression depends on the product pd and is known as Paschen's Law

$$V = \frac{B(pd)}{C + \ln(pd)}, \qquad (1)$$

where $C = \ln A - \ln(1 + 1/\gamma)$. The constants B and C depend on the specific gas used and the probability of secondary electron emission from the cathode, which itself is a function of the energy of the ions impinging on the cathode and the material used for the electrodes. In fact, B and C also depend on α.[13]

Students can experimentally investigate the dependence of the breakdown or starting voltage as the balance between electron production and loss changes. Increasing d decreases the electric field strength, and decreasing 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. Investigating these dc glows allows students to obtain the dependence of the starting voltage on the product of the pressure and inter-electrode distance.

This investigation invites stimulating questions from students regarding the shape of the curve and how well the theoretical curve aligns with the data. As seen in Fig. 3, the experimental points are often shifted up above the theoretical curve because the breakdown voltage is often 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 try 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. Glow discharges exhibit an intriguing spatial structure, as shown for an air plasma in Figs. 2(a)–2(c). 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, such 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. 14). 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 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 [as seen in Figs. 2(a)–2(c)]. Students can change 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 was empirically found to be given by V_i/E, where V_i is the ionization potential of the gas and E is the (local) electric field strength (the waves indicate periodic changes in the local ionization rate). The floating potential from a Langmuir probe can be used to calculate the electric field (see, e.g., Ref. 14).

After breakdown occurs, current flows freely through the plasma. Students can measure the current-voltage relationship for different currents and gas pressures, determine whether it is Ohmic, and compare it to the familiar resistive circuit. Subsequently, students can calculate the power dissipated in the plasma due to resistive losses and compare it to a typical fluorescent bulb or an incandescent bulb.[15] As an example, Fig. 4 shows the resistive losses for an air plasma at low current can be as low as 0.17 mW. We also note that the resistance is quite high at low currents; as more neutral gas atoms become ionized, conductivity in the plasma increases, thus decreasing the resistance.

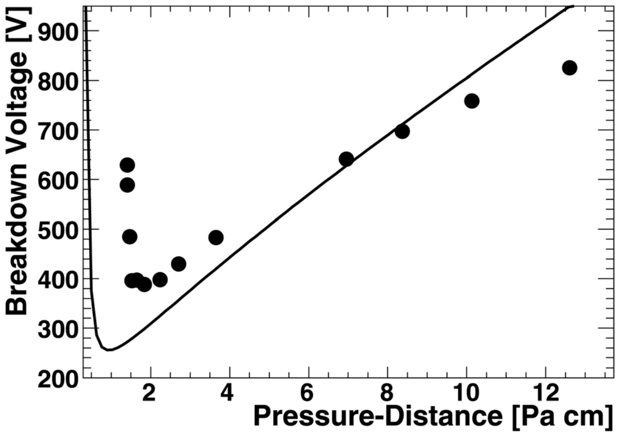

Fig. 3. The electrical breakdown voltage depends on the pressure of the gas and the distance between the high-voltage electrodes (circles, experimental data; curve, Eq. (1) with constants for air).

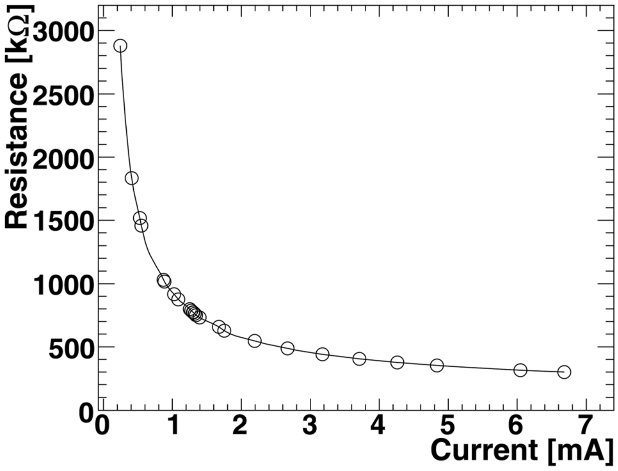

Fig. 4. The relationship between resistance and current for an air plasma at 3.2 Pa (circles, experimental data; curve, fit to Ohm's Law).

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 electron density and temperature.[2] 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.

Students may be challenged to identify possible factors affecting the line intensities observed in the experimental spectra. Such factors in general include excitation probabilities, the mechanisms and the probability of de-excitation, the optical density of the medium, and the response function of the spectrometer. 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. In a dc glow discharge, light is typically emitted by neutral atoms that are excited by electron collisions. If we further assume that electrons collide with atoms in their ground states, then the distribution of the excited levels depends on the electron energy distribution. Experimentally observed line intensities are therefore related to the electron energy, and 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 distribution).

The intensity I_{ik} of a spectral line, corresponding to the transition from an upper energy level k to a lower energy level i, is proportional to $hcA_{ki}n_k/(4\pi\lambda_{ki})$, where λ_{ki} is the observed wavelength, A_{ki} is the transition probability for spontaneous emission, and n_k is the population of the excited states. Under the assumption of a Maxwell-Boltzmann distribution, the population of the excited states n_k depends on the Boltzmann factor e^{-E_k/kT_e} and the quantum degeneracy factor g_k. Taking the logarithm gives a function that is linear in the upper energy E_k

$$\ln\left(\frac{\lambda_{ik}I_{ik}}{g_kA_{ik}}\right) = -\frac{E_k}{kT_e} + C, \tag{2}$$

where the constant C combines all the factors that remain the same for the lines chosen for this plot, such as the instrument function, plasma length, etc. The electron temperature can thus be determined by plotting this logarithm versus energy and finding the slope of the line. The line intensity values obtained from the experimental spectra provide a convenient way of determining the electron temperature.[16]

Several measures can be taken to improve the results of this method. 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 upper states with a broad range of energies. In addition, lines with upper levels excited from metastable levels (common for noble gasses) should be excluded from the analysis because these are dependent on the total number of low energy electrons rather than temperature. For example, in argon the 811.43 nm line is metastable.

We use an Ocean Optics USB2000 spectrometer for a broad survey spectrum of the positive column of argon in a dc glow discharge and a QE6500 for a higher resolution spectrum in the 780–920 nm range (see Fig. 5). The latter spectrum has a high enough spectral resolution to distinguish individual lines, which are used to construct a Boltzmann plot based on Eq. (2) and shown in Fig. 5(c). The measured line intensities are corrected for variations in the quantum efficiency of the CCD detector. The transition probabilities A_{ik} and energy-level information are obtained from the NIST Atomic Spectra Database.[17] Using the reciprocal of the slope of the regression line fitted to the data in Fig. 5(c), we estimate the electron temperature in the positive column to be 0.5 ± 0.3 eV, where the error is estimated from the linear fit.

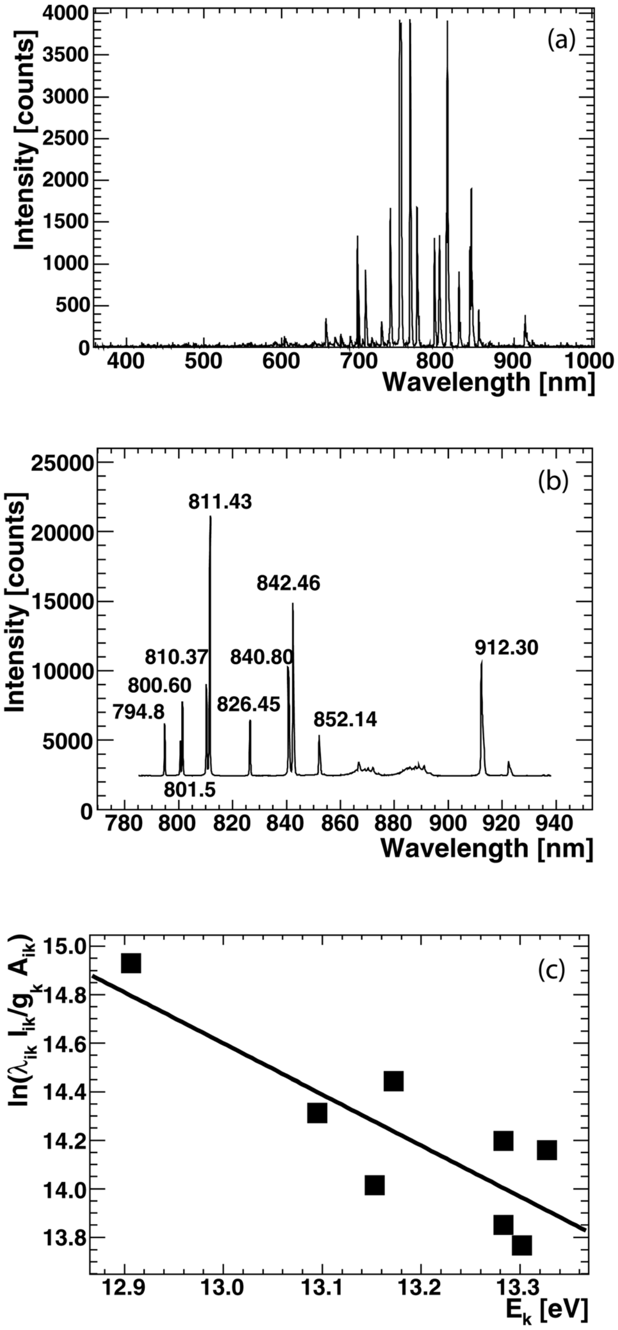

Fig. 5. Survey spectrum (a) and high-resolution spectrum (b) of argon taken in the 780–920 nm range yields spectral lines used to construct a Boltzmann plot (c) in the positive column. The linear fit yields an electron temperature of ~0.5 eV.

We continued to measure the electron temperature throughout the positive column and the negative glow for pressures from 33 to 66 Pa and currents from 10 to 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 when using 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 by exploring the effects of a magnet on the charged particles within a plasma. The ability to "move the light" brings into question all that they know of light, electricity, and magnetism. Furthermore, by bringing a magnet near a plasma, students can visualize the effect of magnetic fields on charged particles.

A current through a Helmholtz coil induces a magnetic field along the axis of the tube, according 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[18] produces a dramatic pinch in the observed light from the plasma. Because 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 the coils must curve back around the coils. Because the charged electrons experience no force in the direction of the field lines they tend to gyrate along the field with radial transport across the field lines greatly decreased. Thus, one can observe that the plasma optical 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 Figs. 2(b) and 2(c)].

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. Driving the Helmholtz coils with a dc current induces a pinch, which is visible in Fig. 6, where we plot the ratio of the cross-sectional area of the plasma inside the coils A_{in} to the area outside the coils A_{out} as a function of the relative strength of the magnetic field $B_z/B_{z,0}$. Here, $B_{z,0}$ is the maximum magnetic field achievable by the Helmholtz coils. As seen in Fig. 6, 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 $0.2 < B_z/B_{z,0} < 0.65$ indicates that the area fraction decreases with a slope of -0.96 ± 0.01 with increasing magnetic field.

Beyond this simple exercise, magnetic fields modify Ohm's law in a plasma with an additional $v \times B$ term (the "Hall Effect"). This effect is substantial in dc glow discharges and can be investigated in an undergraduate laboratory.[19]

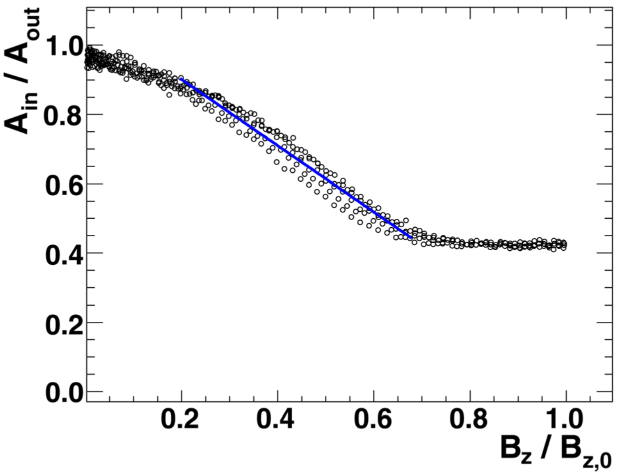

Fig. 6. The ratio of visible plasma area inside A_{in} and outside A_{out} of the Helmholtz coil as a function of increasing magnetic field. The radius of the plasma in the vertical direction was estimated through a moment analysis that fits the visible plasma to an ellipse. The radius was then used to estimate A_{in} for different field strengths (circles). A linear fit (curve) demonstrates that magnetic flux is conserved.

E. Plasma probes

Plasma probe studies allow students to investigate properties of the dc glow plasma such as the electron density, electron and ion temperatures, and potentials inherent in the plasma. Such studies offer 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 electric 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 estimates of the expected Larmor radius and Debye screening length (the latter being $\sim 10^{-5}$ cm, from Ref. 20) of the plasma.[21] Here, we use the most basic of Langmuir probes: the single cylindrical probe. Ours has a diameter of 0.1 mm and an exposed conductor of length 5 mm. (For a straightforward investigation of Langmuir probes using open flames, we refer the reader to Ref. 7.)

While both electrons and ions are accelerated through the potential difference, the electrons reach a higher velocity. In a dc glow discharge plasma collisions with neutral atoms by the ions result in a loss of their kinetic energy because they have approximately the same mass as the neutrals. Collisions between electrons and neutrals result in little loss of speed from the electrons because of their (much) smaller mass. (Compare the energy and momentum balance equations for two particles, one at rest and with a mass 1000 times the other.)

The result is a plasma with electrons at a much higher temperature than the ions and neutral atoms.

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. Therefore, due to the higher mobility of electrons, a probe at the plasma potential will record only an electron current. Just below the plasma potential is the floating potential V_{float}, where no net current is collected by an electrically floating probe. At this lower potential, just enough of the electron current is repelled by the probe so that the ion current to the probe just balances the electron current. Thus, an unbiased probe will record the floating potential V_{float}, whose difference from V_{plasma} is a function of the electron temperature.[22]

In order to study the potentials in the plasma, we start by inserting an unbiased probe into the bulk of the plasma to determine V_{float}. The power supply controlling the bias voltage is then programmed to sweep the probe through voltages around ±20 V from the floating potential in order to span the region well beyond the expected position of the plasma potential and below the ion saturation region.

The current I at each bias voltage V is shown in Fig. 7, where the floating potential was recorded to be -8.4 V. (We note that the apparatus used for the Langmuir probe study used a negative power supply to power the cathode with the anode tied to ground. In this way, all voltage measurements are recorded as Volts below ground.) Following the treatments in Refs. 6 and 24, the plasma potential can be calculated as

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

where m_i is the ion mass, m_e is the electron mass, and T_e is the electron temperature. In order to determine the plasma potential, we need to estimate the electron temperature; this can be determined from the I-V curve in Fig. 7. Just above the floating potential the current is increasing exponentially (because the electron energy distribution is Maxwellian[23]); in this region the average electron temperature depends on the slope of current versus voltage relationship according to

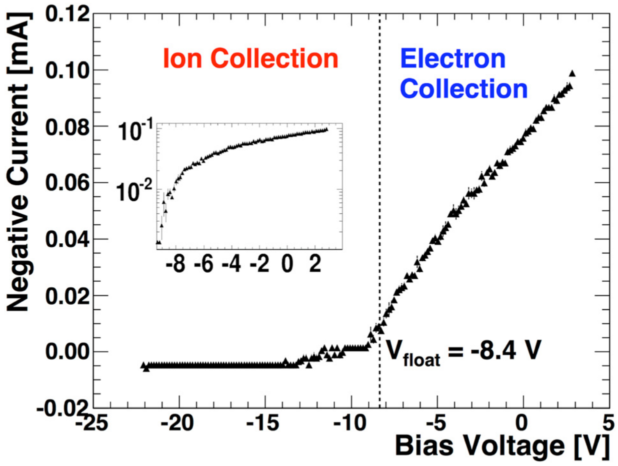

Fig. 7. Data set from the Langmuir probe. Below the floating potential V_{float}, ion current is dominant; above, only electron current is collected. The inset shows the data in the electron collection region plotted on a semi-logarithmic scale.

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

Using this method we find an electron temperature of 0.75 eV, which is reasonably close to the value found in Sec. III C by spectroscopic methods. The discrepancy between the probe and spectrometer results can be accounted for by a number of factors. For example, the perturbations to the plasma due the probe's presence, the electronics used to measure the voltage, and the current drawn out of plasma all contribute to the systematic error. These effects can be mitigated to a certain degree with the use of appropriately sized probes[21] and by averaging over multiple measurements. With extreme care, errors of 20% are possible in the best circumstances.[21] For our results, we estimate an error on the order of the measurement.

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

$$v_j = \sqrt{\frac{8kT_j}{\pi m_j}}, \tag{5}$$

with $j \in \{e, i\}$. Assuming that the ions in our dc glow plasma are predominately nitrogen ions at room temperature ($\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 then 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.

According to a Maxwellian distribution of electron energies, there should be an exponential decrease in the additional electrons collected at the probe as a function of increasing bias voltage above the plasma potential. Experimentally the increase is shown to be linear, suggesting one of two explanations. Either the electrons have an infinite, and equally proportioned, range of electron energies or the effective collection area is increasing and the electron distribution is Maxwellian as expected. The electron velocities do not completely follow a Maxwellian distribution but closely enough to rule out an even distribution. Thus, the linear increase in collection current must be due to an increase in effective collection area. As the probe bias grows above the plasma potential the Debye length grows and attracts electrons further away from the surface of the probe. Eventually, increasing the bias voltage will cause the probe to act as a third electrode for the system, which changes the structure of the plasma. This problem can be avoided by limiting current consumption, using a small probe, and maintaining a bias voltage lower than the anode.

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 introduction 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 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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Carbon Bisulphide Prism

The index of refraction of carbon bisulphide changes by nearly 4% over the range of visible wavelengths. It thus produces a spectrum with a much larger amount of dispersion than typical glasses. To use it with a spectrometer, it is contained in a hollow prism, like this device listed at $6.00 in the 1929 catalogue of the Chicago Apparatus Company. The pure liquid is supposed to have an "ether-like" odor, but most samples are contaminated with remarkably foul-smelling impurities. The prism is in the apparatus collection of Kenyon College in Gambier, Ohio. (Notes and photograph by Thomas B. Greenslade, Jr., Kenyon College)