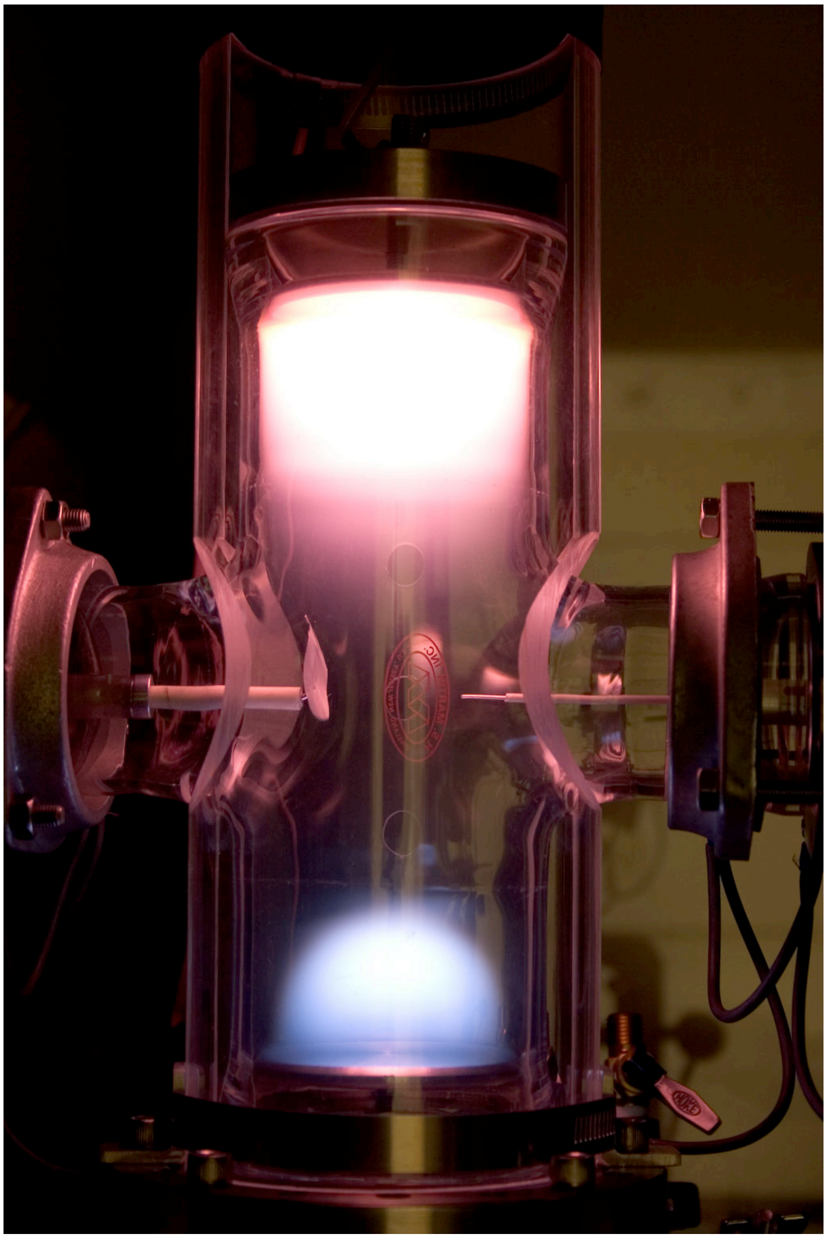
Plasma Lab Manual for Goshen College

Spring, 2005



Plasma in X2

Outline

Acknowledgments

This lab was made possible by the Off-site University Research Support program at the Princeton Plasma Physics Laboratory (PPPL). This is the first time PPPL has made a lab like this for undergraduates, so we are interested in your suggestions about how to improve it. Many of the experiments were based on the those in the PPPL Grad Lab course, which has been taught by Dr. Samuel Cohen for many years.

This lab was designed and tested by Stewart Zweben and built by Mike DiMattia. Also contributing were:, Ron Bell, Tom Holoman, Dave Johnson, Igor Kaganovich, Lane Roquemore Andrew Post-Zwicker, and David Zweben…more names to be added

Summary of Plasma Lab Safety Hazards (see Sec. 2)

1. High voltage:

Never operate the high voltage power supply without the plastic top covers installed on top of the plastic tube to protect you from touching the high voltage electrode at the top of the glass tube.

2. High pressure gas bottles:

Do not remove the gas bottles from their secured positions, or remove the pressure regulators, unless you are specifically trained to handle high pressure gas bottles.

3. Vacuum system:

Be careful not to break the glass which is slightly exposed on the side ports of X2. This could possibly cause an implosion if X2 is under vacuum.

4. Magnetic fields:

Do not use the permanent magnets or magnetic coil in Sec. 5 if you are wearing a pacemaker.

Plasma Lab Manual for Goshen College

Summer, 2005

1. Introduction

"Thinking, alone, can never lead to any knowledge of external objects. Sense perception is the beginning of all research, and the truth of theoretical thought is given exclusively by its relation to the sum total of these experiences." [Albert Einstein, Ref. 1.1].

"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong," [Richard P. Feynman, Ref. 1.1].

1.1 Experiment vs. Theory in Physics

Despite the impression you may have gotten from some textbooks, the ultimate authority in physics lies in experiment, not theory. Also, most discoveries are made through experiments, not through theory; in fact, many great discoveries in physics were made when experiments disagreed with existing theory.

Yet the great success of physics is that most of the regularities observed in Nature can be summarized very accurately in a few relatively simple equations, such as Newton's Laws, Maxwell's Equations or the Schrodinger Equation. Therefore experiments in physics are often designed to find relationships or equations to describe a "Law of Nature". Sometimes experiments are specifically designed to test an equation proposed by a theorist. Some experimental physicists enjoy proving theorists wrong.

There are many ways of doing experiments in physics. Sometimes the goal is to discover new things, such as a gravity wave or a Higgs boson. Sometimes the goal is a practical application, such as an optical switch for a new generation computer. Sometimes the required accuracy is only 10%, sometimes it is 1 part in 10^{12}. There is no simple "scientific method" to do a good experiment; the best way to learn about experiments is to do them, which is the purpose of this lab. Interestingly, the ultimate test of the validity of an experiment is not agreement with theory, but agreement with other experiments, i.e. the results must be reproducible by other experimentalists.

1.2 Plasmas

You have already seen plasmas in lightning bolts, sparks, neon signs, plasma balls (sold in novelty stores), and on the surface of the Sun. Everything turns into plasma above about 10,000 ºC, when the electrons start to break away from atoms and roam around freely.

Perhaps the two most important properties of plasmas are that they conduct electricity and emit visible light. Both of these are due to the high temperature electrons: the free electrons conduct electricity, while the bound “excited” electrons cause the atoms to emit light. You will measure both of these properties in this lab.

Plasmas can have a very wide range of density and temperature, as shown in Fig. 1.1 [1.2]. The plasmas you will make in this lab are similar to those in neon signs and fluorescent light bulbs, with an electron temperature of $T_e \approx$ 1-10 eV ($\approx$ 10,000-100,000 °K) and an electron density of $n_e \approx 10^9 - 10^{11}$ cm^{-3} (about 10^8 times smaller than the density of air at room temperature). The ion temperature is low, however, not much above room temperature (1/40 eV). The electrons and ions are therefore not in thermal equilibrium in these experiments.

Plasmas are used for many practical applications [1.3]. For example, they are used in lighting (energy-saving light bulbs), in displays (neon signs and plasma TVs), in manufacturing (welding and steel making), and in computer chip making (plasma processing). Many people who create and work with plasmas are not physicists but engineers and technicians.

Finally, plasmas can be beautiful and fascinating to watch, as in the aurora (Northern Lights), or in the plasma spheres sold in stores. They seem very mysterious, and usually are.

1.3 Plasma Physics

Although there are several excellent textbooks on plasma physics [1.4-1.6], they contain relatively few examples of excellent agreement between experiment and theory. This is because even the simplest plasmas are difficult to understand in any quantitative detail. In other words, when we do a plasma experiment it rarely agrees with theory to within better than 10%.

This may seem strange at first, since the principles of plasma physics are based on Newton's laws and Maxwell's equations, which are accurate to at least 1 part in 10^6. Plasmas are difficult to understand quantitatively for several reasons:

1) Plasmas are an example what physicists often call "complex systems", which usually means systems with many interconnected variables. For example, the plasma temperature can depend on the plasma density and current, the plasma current can depend on the plasma temperature and density, and the plasma density can depend on the current and temperature, etc. Plasma equations usually have many terms with many nonlinear relationships. Each term adds uncertainty to the experimental situation and difficulty to the theoretical analysis.

2) Plasmas are almost always unstable, since their temperature is very far from the temperature of their surroundings. Instabilities driven by the resulting temperature or density gradients are a major subject in plasma physics, but these instabilities are normally in a "nonlinear" state, which cannot be described by analytic solutions to the basic equations. Real plasmas are usually compared with theory through numerical (computer) simulations, which are themselves often approximate and difficult to understand.

3) Plasma conditions are hard to reproduce exactly from one day to the next (or sometimes even from one minute to the next !). This is usually because the plasma has some contact with a solid surface, and varying conditions in the first few atomic layers on this surface can affect the plasma "boundary condition" or composition. Even the evaporation of a very small speck of surface material can change the plasma composition, since the plasma has such a low density compared with the solid surface.

4) Plasma properties are difficult to measure with an accuracy of better than about 10%, partly because these properties are varying or fluctuating because of (2) and/or (3), but also because the measurements are intrinsically difficult to make. There are good books [1.7] and many papers on plasma diagnostic techniques, but experimental plasma physicists are usually happy with a 10% uncertainty in their measurements.

1.4 Approach in this lab

This lab is designed to give you some hands-on experience in experimental physics, and to teach you some plasma physics. Specifically, this lab should give you experience with vacuum systems, basic electrical measurements, optical measurements and spectroscopy, plasma diagnostic techniques, and data analysis. It will also give you an opportunity to be creative and to design new experiments.

Each of the sections in this manual will ask you to try something, to measure what happens, and then to try and explain it. This manual will not start by giving you the "textbook" explanations for what you see, but it does contain reference material which can help you to understand your results.

Based on the discussion of Sec. 1.3, you should not expect to make your measurements with better than about 10% accuracy. But it is important to keep track of the various types of uncertainties and systematic variations in the data order to estimate how accurate the measurements really are.

1.5 Some questions:

1) How many Nobel prizes in physics were given out for experimental work, compared with theoretical work ? Has there been a trend over the past 100 years ?

2) Say you have a plasma made of Helium with a density of 10^{13} cm^{-3} and a volume of 100 cm^3 contained in a vacuum vessel composed of iron. What size particle of iron would it take, if evaporated into the plasma, to make a it 10% iron plasma ? (assume all the iron is ionized).

References:

1.1 R.P. Feynman, The Feynman Lectures in Physics; Albert Einstein, from speech in 1950, quoted in Physics Today, June 2005 p. 48

1.2 Plasma chart: http://fusedweb.pppl.gov/CPEP/chart.html

1.3 Plasma applications: http://www.plasmacoalition.org/applications.htm

1.4 Introduction to Plasma Physics, F.F Chen

1.5 Introduction to Plasma Physics, R. Goldston and P. Rutherford

1.6 Plasma Physics and Engineering, A. Fridman and L. Kennedy

1.7 Principles of Plasma Diagnostics, I. Hutchinson

Plasma Lab Manual for Goshen College

Summer, 2005

2. Equipment and Safety

This section will describe the main equipment used in the PPPL plasma lab and will tell you how they work. In ***red italics*** will be important safety information concerning these components.

This equipment can hurt you (or someone else) if you misuse it ! Please do not operate any of it until you have read and understood this section. If you have any questions about the safety of this equipment, contact your professor or PPPL.

Other important points not related to safety are in bold blue.

1.1 Introduction

The plasma lab consists of two glass plasma-filled tubes, one at the left of the workbench (X1), and a second larger one at the right (X2). You should start with the experiments described in Sec. 3-7, which use X1, and then move to those of Sec. 8-10, which use X2. Both X1 and X2 use the same vacuum system, gas delivery system, and high voltage power supply. Thus you can not use both X1 and X2 at the same time.

2.2 Vacuum system

Plasmas are much easier to produce in a partial vacuum than at atmospheric pressure. The vacuum pump for this experiment is located on the bottom shelf at the right, as shown in the photo in Fig. 2.1. The vacuum pump is like a water pump, but with tight seals to prevent gas from leaking back into the vacuum side. It is turned on and off using the switch on the right leg of the table. There are no controls on the pump itself; it is either on or off. You can hear it gurgling when it is on. The pump should be turned off when not in use for an experiment.

The vacuum system diagram is shown in Fig. 2.2. The vacuum pump can be connected to either of the experimental glass tubes: tube XI is at the left, and tube X2 is at the right. This pump is a mechanical "roughing" pump, which can reduce the pressure in the tubes to about 10^{-6} times atmospheric pressure, which is sufficiently low for these experiments. The tubes can be vented to air using the valve shown in Fig. 2.3.

The procedure for using this vacuum system is described in Sec. 3.

Our pump is lubricated with special low vapor pressure pump oil. There is an oil level indicator (see-through glass) on the side of the pump; however, it was filled above the level of the glass so you won't be able to see the oil level, since the oil is clear. You will not have to change the pump oil for several years. Note that there is a black toggle switch on the left side of the pump (see Fig. 2.1) which should always be in the "0" position for normal pump operation. The "1" position is for intentionally overheating the pump to remove water vapor from the oil. This should not be needed unless you change the oil.

The vacuum side of the pump passes through an oil trap to minimize the amount of oil vapor which can get into the vacuum system. The pump also exhausts a small amount of pump oil vapor to the room. Although the exhaust has an oil filter on it, as shown in Fig. 2.1, you can sometimes smell the oil in a poorly ventilated room. The oil is non-toxic, but for comfort:

It is recommended that the pump exhaust be vented to the outside air with a small diameter (few inch) flexible tube.

The most dangerous part of the vacuum system is the glass tube, which can implode if it is broken under vacuum, potentially causing pieces of glass to fly around the room. However, this glass is very thick and it will not break unless it is hit hard with a wrench or something. Nevertheless, the glass tubes in this experiment are protected with clear plastic covers, which protect the glass from being broken and, if that fails, prevent the glass from flying around.

Never operate the plasma tube without its clear plastic cover attached. Only remove the plastic covers when the glass is at atmospheric pressure. Be particularly careful not to hit the exposed glass sections between the side ports and main glass tube of X2.

The pressure in each tube is measured by a pressure gauge, shown in Fig. 2.3, which is connected to vacuum pressure meters on the table next to

X1 and X2, as shown in Fig. 2.4. There is one vacuum gauge and one meter for each tube. These are "convectron" vacuum gauges, which measure pressure by the rate of heat conduction from a hot filament (a description of the convectron gauge is in the Supplementary Materials for this section). Note that the pressure reading on the gauge has to be corrected by a "gauge factor" when used with a gas other than Nitrogen; these gauge factors are also given in the Supplementary Materials.

2.3 Gas delivery system

A plasma can be made with room air, but plasmas in this lab are made with pure inert gases to avoid contamination and to make the plasma conditions as reproducible as possible. These gases are contained in the high pressure gas bottles attached to the bottom back of the lab bench. The gases used here are Helium and Neon, which are non-flammable and non-toxic.

The gas bottles have a main valve on top and a pressure regulator attached to the main valve, as shown in Fig. 2.5. The regulator dials indicate the pressure in the gas bottle (typically 1000 psi) and the pressure delivered to the experiment (typically 20 psi). The main valves should be shut tightly when the experiment is not in use, and opened wide when the experiment is in use. The pressure regulator handle is properly adjusted and should not be changed.

The gas delivery system diagram was shown at the left of Fig. 2.2. The gas pressure in each of the tubes is controlled by the rotatable black "needle" valve shown in Fig 2.6. During an experiment, the gas is being continuously fed into the tube and the tube is being pumped out at the same time, so that an equilibrium pressure is reached.

The most dangerous part of the gas delivery system are the high pressure gas bottles, which can become rockets if the main valve is broken and the gas exhausts at high speed. The gas bottles are carefully secured to the lab bench to avoid damage to them and to restrain them. They do have to be recharged periodically with new gas, but this should only be done by someone trained to do this safely.

Do not remove the high pressure gas bottles unless you are trained to handle them safely.

Some additional information about handling compressed gases is provided in the "PPPL Compressed Cryo" files in the the Supplemetary Materials for this section.

2.4 High voltage power supply

The electrical circuit for this experiment is shown in Fig. 2.7. These experiments use a DC power supply capable of supplying 10 mA of current at 3000 volts. This power supply is located in the rack as shown in Fig. 2.8. The voltage can be adjusted using the knobs at the front, and the polarity of the supply can be changed (when the supply is turned off) using a recessed switch at the top of the supply (it needs to be taken out of the rack to do this).

The high voltage comes from the power supply and then goes into an insulated plastic box, also shown in Fig. 2.8, where the current is passed in series through an ammeter and a 100 kΩ □□□□□□or. This resistor (sometimes called a "ballast resistor") limits the current in case of a short-circuit, and also provides stability to the circuit in case the plasma has a negative resistance (which sometimes happens). The voltage drop across this resistor is subtracted from the applied HV to get the voltage across the plasma. This voltage across the plasma itself is measured by the small voltmeter on the right of the box.

The high voltage then goes out of the box to the top of (one of) the experiments, as shown in Fig. 2.9. Since there is only one power supply for both experiments, you will have to attach the cable from the experiment you are working on to this box. The cables from the supply to the box and from the box to the experiments are special high voltage cables and should not be modified except by a trained electrician. The power supply is grounded to the rack, and the rack is grounded to the 110 VAC ground lead which powers all the equipment. The bottom electrode in both experiments is grounded to the metal cart, which is also connected to the rack and grounded through the AC supply.

All voltages above 50 volts are potentially dangerous to people, depending on the level of current which passes through the body. This supply is capable of delivering about 10 mA, which at 3000 volts is high enough to give you a nasty shock and to burn your skin if you touch it. Therefore all parts of the high voltage circuit are protected by the cables and/or by plastic boxes so that they can not be touched.

Never turn on the high voltage supply without first checking that all the high voltage cables and protective covers are connected. Always turn off the high voltage supply when it is not actively being used in the experiment.

Some general electrical safety guidelines are in the "PPPL Basic Electrical Safety" course viewgraphs in the Sec. 2 Supplementary Materials.

2.5 Magnetic fields

The experiments of Sec. 7 use magnetic fields which may exceed the recommended fields for pacemaker wearers. Do not do this experiment if you have a pacemaker.

3. Making a Plasma

3.1 Introduction

The goal of this first experiment is to use the equipment described in Sec. 2 to make Helium and Neon plasmas in the X1 tube. The procedures you will use in this section will be used for every other experiment.

Do not start this experiment unless you have read and understood Sec. 2, especially the parts in red concerning safety issues !

3.2 Initial conditions

Before you start, check that the equipment is in its proper "initial condition", which is the state it should be in when it is not being used. Most of the controls for the gas and vacuum systems are on the front of the bench, as illustrated in Fig. 3.1.

1) main gas bottle valves are both shut off
2) main vacuum valves V1 and V2 are both shut off
3) all valve handles on the front panel are closed (vertical)
4) the high voltage power supply is switched off and set to 000 volts
5) the cable from the HV power supply is connected to the "HV in"

connector at the back of plastic box, and the cable from the "HV out" at the back of the plastic box is connected to the top of X1 through the plastic cap, as shown in Fig. 2.9

6) the vacuum vent valve is closed (knob perpendicular to the tube)
7) the needle valve is closed (all the way clockwise)
8) the separation between the movable bottom electrode and the top electrode is about 5 cm. This separation can be changed by rotating the white plastic wheel at the bottom of X1, as shown in Fig. 3.2

3.3 Making a Helium plasma

1) close the vacuum vent valve
2) switch the vacuum pump on
3) open the main vacuum valve V1. The pressure gauge reading jump off-scale for a few seconds, then fall to about 100mTorr within 10 sec or so, and to then down to about 10 mTorr in about 10 minutes. ***If it doesn't get to around 10 mTorr in about 10minutes, you have a leak which needs to be found and fixed before proceeding any further !***
4) open the valve V1b to pump out the first part of the gas delivery line (see Fig. 2.2); the pressure in XI should initially jump up and then come down to about 10 mTorr in a minute or so
5) open the valve V1a to pump out the rest of the gas delivery line; the pressure in XI should initially jump up and then come down to about 10 mTorr in a minute or so
6) ***close V1b to stop the pumping of the gas delivery line ! If you do not do this the gas will be pumped out before it gets to X1***
7) open the main valve on the top of the Helium bottle to nearly full open
8) open the front panel valve labeled He at the top left (turn to horizontal)

9) slowly open the needle valve and watch the pressure on the gauge rise up to about 1 Torr

10) darken the room lights so that you can see the plasma better, but still are able to read the HV supply dials and see the ammeter

11) turn on the HV supply and increase the fine voltage knob until you can see a light blue plasma ! This should occur at below 500 volts. Increase the voltage until the current in the ammeter reaches about 10 mA. The plasma should look something like Fig. 3.3.

12) you can now vary the pressure (between about 100 mTorr and 10 torr) and the high voltage (up to 3000 VDC) to see the wide range of behavior of this type of plasma. The only constraint is that ***the current through the plasma should not exceed 10 mA for more than 10 seconds or so***, since this overheats the HV power supply.

13) as you are varying the pressure and voltage, you can look for:
    a) changes in the spatial structure of the plasma
    b) changes in the brightness or color of the plasma
    c) fluctuations or instabilities in the plasma

You can record your observations, but we ill investigate each of these in detail in later sections.

3.4 Switching to a Neon plasma

1) turn down the HV knob to zero and shut the HV supply off

2) close the main valve on the Helium bottle

3) close the front panel Helium valve (to vertical)

4) open V1b. The pressure will rise suddenly as the Helium gas pumps out, but then should drop about 10 mTorr in a minute or two

5) **close V1b to stop pumping on the gas line**

6) open the main Neon bottle valve to nearly full open

7) open the front panel Neon valve at the bottom left of the front panel

8) adjust the needle valve until pressure reaches about 1 Torr

9) turn up the HV to about 500 volts until you see a red-purple plasma. Increase the voltage until the ammeter reads about 10 mA. The plasma should look something like Fig. 3.4.

10) you can now vary the pressure and high voltage to see the wide range of behavior for this type of plasma, as in Sec. 3.3 step 11. **Do not exceed 10 mA plasma current for more than about 10 seconds.**

3.5 Shutting down the experiment for the day

1) turn down the HV knobs to zero and switch the HV supply off

2) close both the main gas bottle valves

3) close all the front panel valves (all back to vertical)

4) turn the pump off

5) the pressure in X1 will rise to near atmospheric in about a minute due to some residual leaks in the vacuum system. you can leave the vent valve closed if the experiment will be used again soon. If the experiment will not be used for a while, or if you want to take of the plastic cover of the glass tube, you can open the vent valve and bring X1 tube up to air

4. The Paschen Curve

4.1 Introduction

The Paschen curve is a plot of the DC voltage required to create a plasma as a function of the distance between the electrodes and the pressure in a gas. This curves is important for understanding how we created the plasmas in Sec. 3, and also for the design of high voltage electrical devices (which are usually *not* supposed to make a plasma)!

These curves are named after Friedrich Paschen, the physicist who first investigated this relationship about 1889. There are different Paschen curves for different types of gases, and somewhat different curves for different electrode geometries. In this section you will measure the Paschen curves for Helium and Neon and try to understand them. In later sections you will can to modify the Paschen curves with various techniques.

For this first experiment we will describe the procedures for data taking and analysis in some detail. Subsequent experiments will leave more room to exercise your own initiative and creativity.

4.2 What does it take to ionize a gas ?

Usually its a good idea to think about the experimental situation before you do the actual experiment. In this case, think back to what you did in Sec. 3 and ask yourself: what conditions were needed to create the plasma, or in other words, what did it take to ionize the neutral gas in the tube ?

You might start by thinking about one atom in the Helium or Neon gas. Its electrons are bound with a typical energy of 10 eV; in other words, it takes about 10 eV to ionize a typical neutral atom. What electric field would you have to apply to the atom to remove the electron, given the atom's size of $\approx 10^{-8}$ cm ? Do you think the electric fields were this large in our plasma tube ? It turns out that this "field ionization" process can play a role in some types of plasma formation, but not in our case. Another way the electron can be broken off from the atom is the photoelectric effect, which requires a high energy photon to be absorbed by the atom. Are there photons of $\approx$ 10 eV in our tube ? It turns out that this process can also play a role in plasma formation, but not in our case.

So why does the gas become ionized above a certain voltage ? Before you begin to the experiment it might be interesting to take 15 minutes or so to think of some possible explanations. Write them down and then try to formulate some "theoretical predictions" based on your guesses, which can then be compared with your experimental results. For example, do you expect the voltage required for ionization to increase or to decrease as the pressure is lowered ? To increase or decrease as the electrode spacing is increased ? To increase or decrease from Helium to Neon ?

4.3 Making Paschen curves

4.3.1 Repeat the steps you did in Sec. 3.1 – 3.3, starting with Helium gas. Keep the spacing between the electrodes at the same 5 cm or so, and measure the electrode spacing with a ruler to within about 1 mm. Vary the voltage and pressure to check whether the plasma behaves as it did before (if it doesn't, you may have a leak).

4.3.2 Set the X1 pressure at about 1 Torr and turn the high voltage supply to 000 volts. Darken the room again, but you should be able to read the HV knobs and ammeter. Then slowly increase the "fine" knob on the HV supply until you can see a faint plasma glow in the tube. You should also see a small increase in the current when you see the plasma. Note the voltage when you first see the plasma and current. Now, start making a table of the voltage required to create the first faint light of a plasma vs. the plasma pressure (this is sometimes called the "breakdown" voltage). You don't need to record the current in detail, except to get a rough idea of the plasma current corresponding to the first plasma light.

4.3.3 Repeat this breakdown voltage measurement at least three times at each pressure and write down all your measurements in the table. These measurements are the basic data for this experiment. Then change the pressure using the needle valve, and repeat the voltage breakdown measurements again, making at least 3 measurements at each pressure.

Repeat this for about 5-10 different pressures in the range covering 100 mTorr to 10 Torr (you might find it harder to make a plasma below 200 mTorr or above 5 Torr). You now have the data for one Paschen curve !

4.3.4 Now you are going to change the spacing between the electrodes. First, turn off the high voltage and turn the pressure down to about 10 mTorr by closing the needle valve (not too tightly). Then turn the white plastic wheel shown in Fig. 3.2 to reduce the spacing between the electrodes; start by making the spacing about 2.5 cm instead of 5 cm. Check for transient increases in the pressure while you are turning the wheel – these may be due to small leaks which occur when the shaft holding the electrode is moved through the vacuum seal (this is not a problem as long as the pressure comes back down to where you started from).

4.3.5 Repeat steps 4.3.2-4.3.3 with the new spacing. After you are done with this, change the electrode spacing to about 0.5 cm, and again repeat step 4.3.3 again. If you have time, do this for intermediate electrode spacings, but stay within the range 0.5 cm to 5 cm.

Do not reduce the electrode spacing below 0.5 cm since the electrode might accidentally touch each other and so short out the power supply; do not increase the spacing above about 6 cm since this might damage the rotatable vacuum seal at the bottom of the tube.

4.3.6 After you have finished scanning the electrode position, put the electrode back to its initial position at a spacing of about 5 cm and repeat the measurements you started with at this spacing, but this time take about 30 voltage measurements instead of 10 (this should only take a few minutes). Keep track of which measurements were made at the beginning and end of this longer data taking run. If there are any differences between them it can indicate some type of systematic error in the experimental results.

4.3.7 Finally, switch from Helium to Neon gas, as outlined in Sec. 3.4 and repeat steps 4.3.1 to 4.3.6.

4.4 Initial Data Analysis

After completing Sec. 4.3 you should have a table with at least (2 different gases) x (3 electrode spacings per gas) x (5 pressures per spacing) x (3 trials per pressure), or roughly 100 measurements of the breakdown voltage. With such a large collection of data it is often useful plot up the data in various ways, even in the absence of any theoretical model with which to compare the data. The “old fashioned” (but still good) way to plot data is to use graph paper and a pencil. However, if you have access to a spreadsheet program with graphing capability (such as Excel) you can make the graphs more quickly and neatly.

The simplest way to start is to plot the breakdown voltage on the vertical axis vs. the pressure on the horizontal axis. Do this separately for each different electrode spacing and for each type of gas. You should see a minimum in at least some of these curves, which represents the minimum voltage required to create a plasma for a given distance between the electrodes. You should find that the breakdown voltage increases strongly as the pressure is reduced below the pressure at this minimum, and increases slowly as the pressure is raised above this minimum.

Note that the pressure reading of our vacuum gauge is calibrated for use with Nitrogen gas, and that when it is used in Helium or Neon you need to multiply the reading by a "gauge factor" mentioned at the end of Sec. 2. These can be found in the Supplementary Materials for Sec. 4.

Once you have the data plotted, you should estimate the average "error bar" or uncertainty level is for typical measurements in this experiment. This is best done using the data from the longer run of Sec. 4.3.6. Plot the distribution of measured breakdown voltages obtained in the long run. What is the shape of the distribution of these results ? Generally experimentalists use the term "random errors" to describe variations due to unknown factors, and these generally follow a Gaussian distribution about their average. The width of the Gaussian distribution is typically taken to be the uncertainty in the measurement ("1-sigma"). But was there any non-random or variation between the first trial and the last, i.e. was there any "systematic error" due some subtle changes in the equipment between the first an last measurements ? If so, What do you think causes these variations or uncertainties ?

Error analysis is a major component of all experiments, but we will not discuss it much further here. Suffice it to say that a good experimental paper will contain error bars on all measurements, and some assessment of the possible sources of these errors. This helps the reader of the paper to understand how the accuracy and range of reliability of the results.

Now, see if you can find an empirical formula for the measured breakdown voltage at different pressures and spacings which fits all (or most) of the data for Helium. This would be the kind of formula used by engineers to design electronics to make sure electrical equipment doesn't "break down" when high voltages are applied across various parts of it.

Finally, see if you can find a way to combine the data on the spacing dependence with that of the pressure dependence; in other words, is there some combination of pressure and spacing which, when used as the horizontal axis, causes all of the separate pressure and spacing curves to fall along nearly the same line. Based on your thinking about the experiment in Sec. 4.2, is there some special combination of pressure and spacing makes physical sense as an independent parameter in this experiment ?

4.5 Comparison with existing data

At this point, you should try to compare your results with existing data on Paschen curves for Helium and Neon. Most Paschen curves are plotted with the breakdown voltage on the vertical axis and the product of pressure and electrode spacing on the horizontal axis. You can find such data in the book "Plasma Physics and Engineering", by Fridman and Kennedy, Fig. 4.19. You can also find some references in the

Supplementary Materials section of this manual, or using Google, or using in the Web of Science or some other database of scientific articles.

How close are your results to the Fridman textbook results ? How close are the textbook results to other references, including the original journal articles (if you can find them) ? What factors could make these results different ?

4.6 Explaining the Paschen Curve

The key to understanding the Paschen curve, at least according to the textbooks such as Fridman's, is a process called the "electron avalanche", which causes the breakdown in experiments like ours. In an electron avalanche, a single free single electron accelerates in the applied electric field until it gains an energy of at least 10 eV. Then it collides with a neutral gas atom and ionizes it, which creates a second free electron, both of which then gain another 10 eV and ionize two new atoms, and so on. This exponential process can start to create a plasma, which can then grow (maybe by other processes) to create the steady current of electrons we see in the tube after the initial breakdown ($\approx$ 0.1 mA or 10^{15} electrons/sec).

Although this sounds simple, it is really quite difficult to understand or explain the Paschen curve in detail, particularly if we're looking for an explanation "from first principles" (e.g. based on the atomic physics of the the collisions and the atoms). For example, ask yourself: where did the first electron come from ? What happens if the electrons collide with the atoms before they have enough energy to ionize them ? What happens if the electron doesn't collide with any neutral atoms in the length of the tube ? What happens to the ions in the electric field ? How does the breakdown voltage depend on the atom's ionization potential ? We'll get back to the quantitative analysis in Sec. 4.7.

For a start, try to evaluate the simplest electron avalanche model before you get into the details of the Paschen curve theory. Assume that each neutral gas atom (Helium or Neon) is a hard sphere of diameter ≈0.1 nm, and that the ionization potentials (i.e. the energy needed to remove one electron) are I ≈ 25 eV for both gases (actually, they are 24.6 eV for Helium and 21.6 eV for Neon). The electron will have to gain about 25 eV in the applied electric field before colliding with a neutral atom. What is the mean free path of an electron in a neutral gas of pressure 1 Torr ? Therefore, at what voltage would you expect the electrons to start ionizing the gas when the electrodes are separated by 5 cm at this pressure? How does this compare with your measurements ? Can this simple model explain the pressure and electrode spacing dependences of your date, or the difference between the Helium and Neon results?

4.7 Fits to the Theory of the Paschen Curve

Now you should be ready to read the textbooks and reference papers which describe the conventional theory which explains the Paschen curve. A good reference is Sec. 4.41 and 4.4.2 of Fridman's book.

One of the two main physical elements of this model is the Townsend ionization coefficient "α", which represents the electron avalanche in the form $n_e(x) = n_{e0}\exp(\alpha d)$, where d is the electrode gap length. The other main physical parameter of this theory is, somewhat surprisingly, the secondary electron emission coefficient of the cathode "γ", which represents probability that a secondary electron is generated on the cathode by a single ion impact. It turns out that these secondary electrons emitted at the cathode are needed to sustain the plasma, since otherwise the initial population of electrons will be quickly collected by anode and not replaced fast enough to sustain the discharge.

In case you don't have a handy reference, some formulas relevant for the Paschen curve theory are (taken from Fridman's book):

(a) the Townsend formula for electron balance with a current sustained by secondary electron emission is:

$$\gamma[\exp(\alpha d) - 1] = 0 \qquad 4.1$$

(b) the electric field needed for breakdown can be written using the parameters "α/p" and "E/p" as a semi-empirical expression (i.e. not from a first-principles theory), where p is the pressure:

$$\alpha/p = A \exp[-B/(E/p)] \qquad 4.2$$

Here A and B are the Townsend coefficients, which depend on the gas.

(c) combining 4.1 and 4.2 gives the conventional "Paschen formula" for the breakdown voltage:

$$V=B(pd)/[C+\ln(pd)] \qquad 4.3$$

where the parameter B is the same as in 4.2 but the parameter A has been replaced by $C=\ln(A) - \ln[\ln(1/\gamma+1)]$.

Based on this knowledge you should be able to fit your data on V vs. p to the Eq. 4.3 and find experimental values for the A and B, or the related coefficients α and γ, for both Helium and Neon. Then you can compare you're A and B results to the values given in Table 4.3 of Fridman's book. Fitting data to model curves is a useful skill which now can be done with Excel or similar programs. Don't forget to estimate the error bars on your measurements of A and B.

Here are some questions you should be able to answer about the results and analysis of this first experiment:

1) Why does the breakdown voltage increase rapidly at low "pd" ?

2) Why does the breakdown voltage increase linearly at high "pd" ?

3) How does the minimum breakdown voltage depend on the secondary electron emission coefficient ?

This is the end of the Paschen curve experiment. However, some additional questions and suggestions for further experiments are in Sec. 4.8.

4.8 Open questions and further experiments

As usual in physics (especially plasma physics), the conventional explanation for an experiment is only partially true (or partially accurate), and so there are many “open questions” or “loose ends” which can lead to further understanding. Below is a list of questions about this lab for which we don’t really know the answers. Each of these could become a research project, so don’t worry if you can’t answer them all !

4.8.1 Where do the first free electrons come from ?

You may have noticed that in Sec. 4.6 we assumed that there were already some free electrons in the neutral gas in order to start the electron avalanche leading to plasma formation. Apparently, most of these electrons apparently come from the cosmic ray background, which consists of charged high energy particles coming from far outside the Earth. How many osmic ray particles pass through the gas per second ? (you can Google this). About how many free electrons does each cosmic ray make in our gas tube ? How could demonstrate the influence of cosmic rays in our experiment ?

4.8.2 What caused the variability in the measured breakdown voltage ?

You probably saw a ±10 volt or so variation in the breakdown voltage under apparently identical conditions, and perhaps even a larger variation under the same conditions from the beginning to the end of the experiment. What caused these apparently random changes ? Answers to questions like this often uncover subtle systematic variations in the apparatus, or flaws in the data taking procedure. Here are some possibilities: changes in the temperature or surface condition of the electrodes, changes in the gas composition or flow speed, or variations in speed with which the voltage varied. Can you demonstrate any of these possible effects ? Have you observed any "hysterisis" in this experiment, i.e. once broken down, does the plasma remain when you go below the breakdown voltage ? Why ?

4.8.3 How long does it take for the gas to break down ?

It is surprising how nonlinear the breakdown process is: a very small change in voltage creates a very large and rapid change in the gas. Although this seems to be explained by the electron avalanche process, we never made any quantitative measurements which confirmed that this avalanche process was actually responsible for breakdown. If the breakdown is caused by a simple electron avalanche model as described in Sec, 4.6, how long would it take ? How would this time vary with pressure ? Can you figure out a way to measure the time it takes for the gas to break down in our experiment ? You can try to do this in a later section using the X2 tube. For further information, see the paper about "Ionization cascade" in the Supplementary Materials.

4.8.4 How can you change the breakdown voltage of a gas ?

This is actually a practical question, since many electrical devices can be damaged by unexpected breakdown. On the other hand, sometimes it is desirable to breakdown a gas at the lowest possible voltage, e.g. in magnetic fusion research. What could you do to change the breakdown voltage in an experiment like ours ? What factors in the theory would suggest a way to change the Paschen curve for a given gas ? Would the breakdown voltage be lowered by adding a source of free electrons with a hot filament ? With a UV light ? What would be the effect of a magnetic field ? You can try some of these things in subsequent experiments using the X2 tube.

4.8.5 Applications

Using what you have learned, what voltage is needed to breakdown room air across a 1 cm electrode gap ? Across a 1 mm gap between your finger and a doorknob (after walking on a carpet) ? To make a 1000 ft. long lightning bolt ? To make a plasma in a pixel of a plasma TV display ? For the latter, the situation is complicated by the presence of the glass walls, but you can Google what type of gas and pressure is used to make the light. It is interesting to note that the process of lightning breakdown in the atmosphere is not really well understood (see article in Supplementary Materials).

Plasma Lab Manual for Goshen College

Summer, 2005

5. Plasma Properties

5.1 Introduction

Our type of plasma is called a DC discharge, or “glow discharge”, and is similar to a neon sign or fluorescent light plasma (the word “discharge” refers to a capacitor discharge which was sometimes used to create the plasma). The structure and properties of these plasmas have been studied for almost 100 years, but there is still active research being done on them. Good textbook references are listed at the end of this section. Some papers on glow discharges can be found in the Supplementary Materials.

In this section you will observe some of the basic properties of these plasmas and try to understand them by learning some plasma physics. The experiments of this section will be somewhat qualitative rather than quantitative, since you don’t yet have the capability of measuring the plasma properties directly. You will make direct measurements of the similar X2 plasma using a Langmuir probe in Sec. 8.

5.2 Structure of the glow discharge

A good place to start is to make sketches or photographs of the structure of the discharge as a function of gas type (Helium or Neon), gas pressure (≈ 10 mTorr to 10 Torr), and applied voltage (from breakdown up to a maximum of 10 mA plasma current). Start by following the procedures outlined in Sec. 3 for making a plasma. Initially it would be enough to note the basic trends, such as the location of the dark and bright regions, the relative brightness of these regions, color changes, unusual spatial features (e.g. spots, radial constrictions, or asymmetries), and instabilities (time varying fluctuations). **Note that the top electrode is the "cathode" (negative voltage) and the bottom electrode is the "anode" (ground).**

Write down the pressures and voltages any time you see something especially interesting. While you are doing this, compare your observations with the standard drawing of the structure of a glow discharge reproduced in Fig. 5.1 (taken from "Becker talk.pdf" in Supplementary Materials). You might have trouble seeing all the features shown in Fig. 5.1, but try to identify things the best you can. At this point you might look on the web for interesting and beautiful pictures of various other types of glow discharges. Some examples are in the Supplementary Materials, e.g. "glow discharge #1" and "glow discharge #2".

The structure of the glow discharge is surprisingly variable and complex. Part of this complexity is due to the atomic physics of the gas; for example, these gases will not emit much light unless the electron temperature and density are at a certain level (this is basically what causes the light and dark band structures). Another part of the complexity is due to the plasma physics, particularly the electron acceleration and collision processes in the gas. A third part of the complexity is due to the electrodes, which can sometimes have a surprisingly strong effect on the discharge, e.g. due to secondary electron emission.

5.3 Electrical characteristics

One of the most fundamental properties of a plasma is its ability to conduct electricity. Pick a gas and a pressure (say Helium at 1 Torr), and measure the current vs. voltage relationship of the plasma using the meters in the plastic box. The ammeter and voltmeter in the plastic box measure the current and voltage across the plasma (remember that the plasma circuit includes a series R=100 kΩ series resistor, so that the voltage you apply at the power supply is higher than the voltage across the plasma). Try the same measurements at a higher and lower pressure, and plot up the results. They should look something like Fig. 5.2. Then try to keep the voltage fixed (say 1000 V at the power supply) and vary the pressure. Plot up these results also. Did you notice any correlation between the plasma current and the visual appearance of the plasma ?

Based on your measurements, what is the electrical resistance of the plasma in units of Ohms ? You should find that the electrical resistance varies quite a lot from the lowest to the highest currents, e.g. from ≈250 kΩ just above breakdown to about 100 kΩ near the highest current of 10 mA. Thus the plasma certainly conductivity increases with discharge current, and the plasma does not act like a simple resistor. How high is the resistance of this plasma compared to a rod of copper or graphite of the same size ? You should find that the plasma is very resistive compared with these metals.

The plasma resistance is the series effect of the various regions of the discharge, so much of the voltage drop across the plasma is due to near-electrode regions with particularly high resistance, as illustrated in Fig. 5.1. From the total voltage and current you also can calculate the electrical power which is being put into the plasma. Is this plasma an efficient light source ? Maybe not in our case, but similar glow discharge plasmas are used in fluorescent lights and neon signs, and can be quite efficient compared with incandescent lights (but not LED's).

5.4 Plasma density and temperature

The two most important plasma parameters are the plasma density and temperature. In general, the plasma electrons and ions can each have their own density and temperature,; however, plasmas like ours almost always "quasi-neutral" (except near the electrodes), so there is rarely any significant difference between the plasma electron and ion density. Thus we just say "plasma density", meaning the density of either species. However, there can often be a large difference between the electron temperature and the ion temperature because the ions and electrons do not collide fast enough to equilibrate.

Before you read further in this section, try to guess what the plasma density and electron and ion temperatures are in our plasma. For example, you might assume that the plasma density can't be much higher than original gas density, and that the total pressure (temperature times density) can't be much higher than atmospheric pressure (or else the vessel would burst). Which is hotter, the electrons or ions ? Can you infer anything about the plasma density or temperature from your measurement of plasma conductivity ? This kind of educated guesswork is an important part of physics.

Now that you have made some guess about the plasma parameters, try to think of a way that you can actually *measure* the density and temperature of the plasma. There are many ways but none of them are very easy. We will do one type of measurement in a later section using X2. Many people have worked for many years to develop methods to measure plasma properties like these, but it is difficult to get better than a 10% accuracy.

Some typical plasma parameters measured for this type of glow discharge in a tube are shown in Fig. 5.3 (adapted from Table 7.1 in the book by Fridman). The values in **blue** are roughly what we get with our glow discharge in X1.

5.5 Collisions

Probably the most striking variation you saw in the structure of the discharge was the variation with pressure. As the pressure was raised the bright glow moved near the cathode and became narrower. In general, a higher pressure lowers the mean free path of electrons and causes a smaller spacing between the various features in Fig. 5.1.

Collisions between electrons, neutral gas atoms, and ions play an important role in all types of plasmas. At this point you can try to understand the structure of the plasma you saw in Sec. 2 and the electrical resistance you saw in Sec. 3 based on quantitative analysis of various collision processes. You can find formulas for various collision processes in the textbooks listed at the end of this section, in the paper by Braithwaite in the Supplementary Materials, or in the valuable Naval Research Laboratory (NRL) formulary (which is on the desk of every plasma physicist, and also in the Supplementary Materials).

To evaluate any of these collision processes you need to know the density and/or temperature of the plasma species involved in the collision. For the sake of concreteness, use the values in **blue** in the Fig. 5.3 for our X1 plasma. Here are some questions you can try to answer about plasma collisions and their effect on the discharge structure:

1. What is the ionization fraction of our plasma, i.e. the ratio of plasma density to neutral gas density? Assume the neutral gas is at room temperature to estimate the neutral density given the gas pressure. What is the plasma pressure (2nT) compared with atmospheric pressure ? Compared with the neutral gas pressure ?

2. What is the average mean free path for electron collisions with neutrals ? You can assume a neutral atom cross section of $5\text{x}10^{-15}$ cm^2. Do you think this distance corresponds to any of the structure you saw in Sec. 5.2 ?

3. Can you estimate the plasma density from the electron-neutral collision frequency and plasma current ? You will need to estimate the average drift velocity of the electrons in the direction of E, which is different from the electron thermal speed (as in a metal). You can also try looking up the conductivity of a weakly ionized plasma.

4. How much of the input power (which goes mainly into the electrons) is transferred to the ions and neutrals by collisions ? From this, can can you estimate the ion and neutral temperature ?

5. Can you estimate some of the factors affecting the balance of electron and ion creation and loss processes in this plasma? In steady state the total ionization rate must be equal to the loss rate. The ionization rate as a function of plasma density and temperatures is shown in Fig. 5.4. The loss rate may depend on the particle confinement or on the process of recombination of electrons and ions.

The answers to some of these questions can be found in Fridman's textbook and the papers in the Supplementary Materials.

5.6 Strange structures

Perhaps the strangest structures in this type of plasma are the small bright spots visible on the anode surface at a pressure of about 3 Torr, as shown in Fig. 5.5. There are sometimes only one or two, but under slightly different conditions an ordered array of 10 or more spots can appear just above the surface of the anode (bottom electrode). Sometimes they are nearly stationary and other times they can rotate slow or very fast. Similar spots can be seen in photos in the presentation by Becker and in “anode spots #1” paper, in the Supplementary Materials. It is really strange that the spots can spontaneously form ordered array, but this is type of “self-organization” is actually rather common in plasmas. Some papers on these structures is in the Supplementary Materials for this section.

References:

text: Fridman and Kennedy, “Plasma Physics and Engineering” (Ch. 7)

text: Lieberman and Lichtenberg, Principal of Plasma Discharges and Materials Processing (Ch. 14)

text: Chen, “Introduction to Plasma Physics and Controlled Fusion”

glow discharge pictures:

http://www.exo.net/~pauld/origins/glowdisharge.html

http://www.itp.nsc.ru/LAB41/Gallery/Gallery-Striations.html

Plasma Lab Manual for Goshen College

Summer, 2005

6. Spectroscopy

6.1 Introduction

This section will introduce you to optical spectroscopy, which an important part of plasma physics (and physics in general). You will make measurements of the wavelengths of light emission from the Helium and Neon plasmas in X1, and compare your results with the expected spectra for these elements, and with the emission from other light sources. The measuring instruments will be simple but the principles are the same as used for research instrumentation.

6.2 Diffraction gratings and spectrometers

The goal of optical spectroscopy is to determine the wavelength distribution of the light emitted from a light source. The instrument to do this is called a spectrometer. The most important part of a spectrometer is the component which separates the light into different colors, i.e. the dispersive element. This can be a prism (as used by Isaac Newton in his experiments on light) or (in most modern spectrometers) a diffraction grating.

A diffraction grating is just a flat surface with fine lines on it spaced about one wavelength of light apart. There are two basic types of gratings: transmission gratings (in which the light goes through the grating), and reflection gratings (in which the light is reflected from the grating). Before going any farther in this experiment you understand how a diffraction grating works (see the Supplementary Materials or any optics textbook).

A spectrometer is any instrument used to make a quantitative measurement of the wavelengths of light. Ideally a spectrometer should be able to measure quantitatively the amount of light at each wavelength over some range, for example, over the part of the spectrum visible to the eye ($\lambda \approx 400 - 800$ nm). The simple spectrometers used in this lab will be able to identify the approximate wavelengths but will not give quantitative information about the intensities.

There are three diffraction grating spectrometers which you can use in this experiment. The simplest is just a card with a "holographic diffraction grating film" from Edmund Industrial Optics, Inc (part H01-307). This is a clear plastic film about 1" wide and 0.003" thick on which there are "ruled" 500 lines per mm (i.e. 2000 nm apart). The second is a "Project Star" hand-held spectrometer, also from Edmund Scientific (see instruction booklet which comes with the lab). The third is a somewhat more sophisticated (but pretty old) hand-held spectrometer from Schoeffel optics.

6.3 Measurement of plasma spectra

Make a Helium plasma in X1 as described in Sec. 3. Adjust the pressure and voltage so that the plasma is as bright as possible, but always of course limiting the current to 10 mA maximum.

Start by darkening the room and looking at the plasma through the 1" card with the diffraction grating from a distance of about 6" to 1 ft. Adjust the angle of the grating and the angle of your eye to maximize the clarity of the colored bands. You should see bands of red, orange, blue-green, and violet, somewhat mixed together since each color forms a wide band. Notice that these colors are ordered according to the wavelength of their light. What determines the width of these bands ?

To help answer this question, tape some dark paper onto the plastic cover to form a "slit" through which to view the plasma light, as shown in Fig. 6.1. Vary the width of the slit from about 1 cm to about 1 mm. You should see the width of the colored bands decrease to form "lines" as the slit width decreases. So the width of the bands is due to the finite width of the light source. Since the wavelength of the light in a spectrometer is determined by the position of these "lines" in the spectrum, a very accurate determination of the wavelength requires a very narrow slit. Unfortunately, as the slit becomes narrower the brightness of the line decreases, so there is a trade-off between wavelength resolution and sensitivity in a spectrometer.

Now use the Project Star spectrometer to measure the wavelength of these colors with the built-in scale. Follow the instructions in the booklet;

for example, check the calibration by looking at a fluorescent lamp. This spectrometer also has a built-in slit, so you don't need to make one yourself. You probably will need to illuminate the scale at the front of the spectrometer with some white light, so that you can read the scale and see the colored lines from the plasma at the same time. If you do this, be sure to turn on and off the plasma to check that the lines you see are from the plasma and not from the white light. Write down the wavelengths of all the lines you can see and indicate their relative brightness. Of course, this brightness is not a quantitative

Finally, use the Schoffel spectrometer to measure the wavelengths of the dominant lines from the plasma. This device already has a 1 mm slit, so you don't have to make one yourself. The rotating screw adjustment is calibrated to read directly in nanometers; check the calibration using a floursecent bulb as for the Project Star spectrometer.

From these measurements you should have a list of at least 4-5 spectral lines characteristic of Helium, along with a qualitative estimate of their relative brightness. Now, compare your list with the data in the Supplementary Materials file "Helium Spectrum", and in Table 1 of "Line Spectra of Elements". How close did you come to the accepted wavelengths of the brightest lines ?

Now, repeat these spectroscopic measurements for a Neon plasma (see Sec. 3 for how to make the plasma). The Neon spectrum is much more complicated than the Helium spectrum, due to the larger number of electrons in the atom, so you should just note the wavelengths of a few bright lines.

If you have more time, you might try to make an "air" plasma (mainly Nitrogen and Oxygen). Vent X1 vented to air and then close all valves; then slowly open valve V1 until the pressure in X1 gets down to about 3 Torr. Then close V1 and turn on the HV power to see the plasma. The pressure can be reduced further by opening valve V1 again, but it can not be increased except by briefly cracking open the vent valve.

6.4 Interpretation of the spectra

The interpretation of these spectral lines is done using atomic physics, which is quantum mechanics applied to electrons bound in atoms. In principle, the quantum mechanical energy levels of any atom can be calculated from the Schrodinger equation given only the atomic number of that atom. In practice, only the simplest atomic spectra can be calculated this way due to the complexity of multi-electron interactions. Even the Helium spectrum with only 2 electrons is quite difficult to calculate, but its energy levels are accurately known and organized into "energy level diagrams", which you can read about in any quantum mechanics textbook. The spectral lines result from electron transitions between these energy levels, and their wavelength depends on the energy difference between the initial and final electron energy levels.

6.5 Plasma diagnostics using spectroscopy

In order to emit light, the electrons in an atom must be “excited” to a higher energy level than their normal “ground state”. In our case the electrons in the gas atoms are excited by collisions with the free electrons in the plasma (the ions can also do some excitation, but not much in our case).

The simplest use of spectroscopy as a plasma diagnostic is to determine the composition of the plasma (or more precisely, the composition of the gas which has a plasma component). From your measurements of the spectrum of pure Helium and Neon you can see that their spectral lines are quite different; thus in principle you can measure the amount of Helium or Neon in any plasma by measuring the brightness of the spectral lines of these elements. However, it should also be pretty clear that the brightness of the spectral lines depends on other factors besides the atom density; for example, the excitation will depend linearly on the plasma electron density. In general, the light emission from a group of atoms at a wavelength λ is:

$$B(\lambda) = n_e\, n_o\, f(n_e,T_e)$$

where n_e is the plasma electron density, n_o is the density of the atoms which emit this line, and $f(n_e,T_e)$ is a function of electron density and temperature specific to this particular transition, such as illustrated in Fig. 6.2. Thus to infer n_o from the brightness we would also need to separately measure n_e and T_e.

Another use of spectroscopy as a plasma diagnostic is to measure the electron temperature. This can be most easily done by measuring the ratio of the brightness of two lines of the same species in the same region; roughly speaking, the larger the electron temperature, the larger the brightness of the lines which require a higher excitation. However, such line ratio measurements can be quite difficult to interpret, as you can see in the paper by Boivin et al in the Supplementary Material.

6.6 Open questions and further experiments

If you have time, you might try the following additional experiments and/or research topics related to plasma spectroscopy.

6.6.1 Changing colors of the plasma

As you vary the gas pressure and voltage in a Helium or Neon plasmas, do you ever notice any change in the color of the plasma (by eye) ? What do you think causes this change ? Try looking at the different colored regions with one of the spectrometers to determine if it is due to new (non-Helium or Neon) lines, or to a change in the ratio of the these lines.

6.6.2 Search for Helium ions

The discussion of Sec. 6.4 and 6.5 did not specify the ionization state of the Helium atom. Are the lines you see in our plasma those of a neutral Helium atom, or those of a Helium ion (i.e. singly ionized Helium atom) ?

If you think they are from a neutral Helium atom, why don't you see lines of the Helium ion ?   Look in Google or elsewhere to find the brightest lines for the Helium ion, and search for them using our spectrometer.

Supplementary Materials:

Helium Spectrum:

http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/atspect.html

Neon Spectrum:

http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/atspect2.html

Diffraction Grating:

http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/grating.html#c2

Line Spectra of the Elements:

http://www.pitt.edu/~n3lsk/linespecproc.html

Plasma Lab Manual for Goshen College

Summer, 2005

Sec. 7: Magnetic Field Effects

7.1 Introduction:

Magnetic fields can sometimes have a big effect on plasmas. In this section you will see how magnetic fields can affect our plasma and then try to understand why. Many of these effects are surprising and difficult to understand, so this a somewhat "open ended" experiment (fusion scientists have been working for 50 years to understand magnetized plasmas !).

The experiments of Sec. 7 use magnetic fields which may exceed the recommended fields for pacemaker wearers. Do not do this experiment if you have a pacemaker.

7.2 Effect of a transverse magnetic field:

In this section you observe the effects of a magnetic field on the plasma in X1 under various conditions. We'll start with the permanent magnet which is 2" x 2" x 0.5", which has its magnetic field the B field vector perpendicular the large plane surface of the magnet.

This is a very strong magnet, so don't let it get within about 6" of your credit cards or it may destroy their magnetic strips. Also, don't let the magnet get near a flat iron surface or you may not be able to remove it !

Given the fact that the permanent magnet will be located on the side of the plasma, it will largely make a transverse magnetic field (perpendicular to the direction of the current in the plasma). In the experiments below you should note the direction and location of the magnetic field and write down the qualitative trends and effects on the plasma that you see.

Start by making a fairly bright and fairly uniform Helium plasma as described in Sec. 3, keeping the plasma current to about 5 mA or so. Now, bring the permanent magnet up close to the plastic cover and observe what happens to the plasma as you change the magnet's position and angle. Is the magnet's effect strongest at the top (anode) or bottom (cathode) ? What happens to the plasma current ?

Now vary the gas pressure from the lowest to the highest pressure at which you can make a plasma. How does the pressure influence the magnetic field effects ? Now, pick a pressure and vary the voltage. How does the voltage (or maybe the current ?) change the effect of the magnet on the plasma? Can you completely extinguish the visible plasma with the magnet ? If you can do this, check what happens to the plasma current.

7.3 Strength of the permanent magnet's field:

The interpretation of the effects in Sec. 7.2 depends on the strength of the magnetic field. You should now try to measure the strength of the magnetic field of this magnet using a small coil of wire and the oscilloscope.

Move the coil across the magnet at a know distance and observe the pulse of voltage on the scope. The voltage is related to the magnetic field by (in mks units):

$$V(\text{volts}) = N(\text{turns})\ A(\text{m}^2)\ \Delta B(\text{Tesla})/\Delta t(\text{sec})$$

where N is the number of turns in the coil each of which has an area A (m^2), ΔB is the change in magnetic field in units of Tesla (=10,000 Gauss), and Δt is the time over which this change occurs (which you can estimate from the scope). Make a plot of B vs. the distance from the plane of the magnet at its center.

7.4 Connecting the electromagnet:

Now you are going to slightly modify X1 to see the effect of a magnetic field in the vertical direction (which you could not do with the permanent magnet).

First, shut off the HV power supply and unplug the connection between the top electrode of X1 to the plastic meter box. Now, slide up the brown cap from the top of X1 over its connecting wire but do not yet touch the top electrode (that is, the stainless disk with the “Danger High Voltage” stickers on it !).

Just to be sure that there is no residual charge on this plate, take the “ground stick” mounted near (which is firmly connected to ground potential), and briefly touch it to the top electrode (without touching the electrode with your finger first !). Touch the steel part of the electrode and not the paper labels.

Now you can unscrew and remove the HV lead connected to the top electrode. Then put the copper magnet coil shown in Fig. 7.1 over the plastic cover on X1 and let it rest at the bottom. Finally, reattach the HV lead to the top of X1, reattach the cover over X1, and reattach the other end of this lead to the back of the plastic box.

Now hook up the magnet coil to the low voltage power supply shown in Fig. 7.2. This is a 24 volt, 5 amp DC supply which is not dangerous; (nevertheless, avoid touching the leads when it is activated). It is activated by the push-button switch on the top, so is normally “off” until you push the switch, which will flip back to “off” when you release it.

After you have hooked the coil up, and with the coil still resting at the bottom of X1, push the switch to turn on the coil for about 10 seconds (still with no plasma). It will make a clicking sound when turning on, and you will also hear internal fan when it is on. How can you tell if the coil is making a magnetic field ? Energize the coil again and **slowly** bring the permanent magnet within a **couple of inches** of the coil until you feel the magnetic force of the coil on the permanent magnet.

This coil can become hot if the current is left on for more than about 30 seconds ! Do not energize the coil for more than about 10 seconds per minute. You can touch the coil when it is not energized to feel its temperature. If it feels hot to the touch, wait until it cools off before energizing it again.

7.5 Effect of an axial magnetic filed:

The electromagnet will largely make a axial magnetic field (along the direction of the current in the plasma), although its strength will vary with the distance from the coil center. In the experiments below you should note the location of the coil and write down the qualitative trends and effects on the plasma that you see.

Now, make a Helium plasma as you have done before using the instructions in Sec. 3. Start with a plasma at about 1 Torr and 1000 VDC of the see what the effect of the magnetic field of the coil is on the plasma. Keeping the coil at the bottom of XI (near the anode), energize the coil for about 10 seconds and see what happens.

Leaving the magnet at the bottom, now vary the gas pressure from the lowest to the highest pressure at which you can make a plasma. How does the pressure influence the magnetic field effect ? Now, pick a pressure and vary the voltage. How does the voltage (or maybe the current) change the effect of the magnet on the plasma? Now, raise the magnet by hand from the bottom to the top of the plasma column (you can touch the insulated coil wires when it is energized). Is its effect stronger or weaker at the top electrode (cathode) ?

Now look to see whether the current changes due to the magnetic field. Do you think the polarity of the coil will affect the results ? Try changing the coil polarity and see for yourself.

If you have time, you can repeat these experiments with Neon.

Finally, take the coil off from X1 and measure the strength of its magnetic field using the method of Sec. 7.3. Compare with the results you expect for this coil, which has about 600 turns with a current of 2 amps.

7.6 Interpretation of the magnetic field effects:

The basic effect of a magnetic field is to introduce another force on the free electrons, F_M=eVxB, where v is the velocity of the electrons. This is in addition to the forces due to the electric field F_E = eE and the various collision processes F_C. Since the magnetic force is dependent on the velocity of the moving charge, the magnetic force on the ions is negligible in this experiment.

Assuming for the moment that the collisions are negligible, see if you can evaluate the B field needed for the magnetic force to dominate the electric force in this experiment, assuming E=100 Volts/cm and an T_e = 1 eV. It may help you to use the long version of the "NRL Formulary", which contains a summary of electromagnetic units (see Supplementary Materials). How does this compare with your observations on X1 ?

If the magnetic field dominates the electric field, what is the trajectory of motion of electrons in the magnetic field ? If you do this calculation you should discover the concept of a "gryoradius". What would be the approximate electron gyroradius in the magnetic field in our experiment (assume B= 300 Gauss) ? How big is the electron gyroradius compared with the plasma size ?

In the case where the gyroradius is much smaller than the plasma and collisions are negligible, the motion of electrons when the electric field is perpendicular to the magnetic field is actually a drift velocity at constant speed in the direction perpendicular to both B and E. This "ExB drift" velocity is $V_D = 10^8$ E(V/cm)/B(Gauss). What is V_D for our experiment ? How big is this compared with the thermal electron velocity V_{th} ? The motion of electrons when E is along B is unaffected by B, since the magnetic force only acts when V is perpendicular to B.

Now, under what conditions can you assume that collisions are negligible for electron motion in this experiment ? You might start by to comparing the collision frequency of electrons with the neutral atoms (see NRL Formulary) with the electron gyro frequency, and so estimate at what pressure a collision will occur before a gyro orbit is completed. If this is the case, the electrons will not simply follow the trends discussed above. What will happen to the magnetic field effects at very high collision frequency ?

Given these simple estimates, you should be in a position to interpret at least some of the observations you made in Sec. 7.2 and 7.5. Make a list of your main observations and trends, and see how well the you can explain them using the simple estimates above.

Of course, you won't be able to explain everything you see. For example, the increase in the current when the magnetic field is perpendicular to the plasma is apparently due to an increase in the axial electric field, according to the paper "B effect on glow 1" in the Supplementary Materials. Similarly, the increase in light emission with a magnetic field may be due to an increase in Te, according to the paper "B effect on glow 2" in the Supplementary Materials.

7.7 Effect of B on breakdown voltage

Now that you have done some experiments to see the magnetic field effects on the plasma, and have thought a bit about why this occurs, here's a chance to test your understanding: can you predict what the effect of a magnetic field will be on the breakdown voltage ? In other words, how does a magnetic field affect the Paschen curve (Sec. 3) ? You should consider both the cases with B perpendicular to the plasma current.

Now, go back and try some of the Paschen curve experiments but now with a magnetic field applied before breakdown. How well did you do in your predictions ? If you didn't get it right don't feel too bad: the effect of a magnetic field on breakdown is still under active research (see "B effect on breakdown" in the Supplementary Materials section).

Sec. 8: Langmuir Probe

8.1 Introduction:

This is the first experiment for the X2 tube. The main difference between X1 and X2 is that X2 allows you to insert various probes into the plasma from the side. These probes can be removed or modified to do more complex experiments than can be done with X1. The X2 plasma is larger than X1, but its electrodes can't be moved during the experiments.

Be careful not to hit the exposed glass sections between the side ports and main glass tube of X2.

The Langmuir probe (sometimes called an electrostatic probe) is probably the most important diagnostic for low temperature plasmas. It is named after Irving Langmuir, who was a pioneer in plasma physics (and other fields of applied physics). A Langmuir probe is basically just a small metal wire stuck into the plasma. You can use it to measure the plasma potential, plasma density, and electron temperature. A simple theoretical model for the Langmuir probe is described in the sections below, with more detail in the Supplementary Materials. However, the details of an "exact" theory for any given type of probe and plasma can become extremely complicated and uncertain, particularly in the presence of a magnetic field (see Hutchinson's book).

8.2 Measurement of the floating potential:

Start with X2 vented up to air and mount the single-tip Langmuir probe onto X2 as shown in Fig. 8.1. At the same time, mount the double probe into the other side of X2 for later use, also shown in Fig. 8.1.

The single probe tip should be approximately in the center of the tube. Attach a BNC cable from the end of the probe to the oscilloscope (if you are not familiar with the scope, check its operation using the signal generator).

Before pumping down X2 with any probe attached, make sure that the O-ring seal on the probe shaft is screwed down tight (with fingers only, not a wrench), and that the clamp is tightened just behind the O-ring seal. This will prevent the probe from getting sucked into the tube under vacuum.

Now, pump down X2 and fill with Helium gas the same way you did for X1, but using the X2 valves. You should reach a pressure of about 10 mTorr within a few minutes. Note that now you need to read the pressure on the X2 meter !

Before proceeding further, make sure that the HV cable at the top of X2 is connected to the plastic meter box (i.e. remove the X1 cable). This is important so that you know where the HV is connected at all times.

Now turn up the Helium pressure to about 300 mTorr and turn on the HV to make a plasma, as you did in Sec. 3. You should see a plasma at about 1000 volts (on the supply). As usual, do not exceed a plasma current of 10 mA.

Now, set the scope for "DC coupling" and measure the DC potential of the probe tip in volts. Note that the scope has a very high input resistance (1 MΩ) so there will be a negligible amount of current drawn from the probe tip. This way is called the "floating potential" because the probe tip is "floating" and not fixed in voltage. The floating potential measured this way is the voltage at which the probe tip collects an equal number of electrons and ions, since there is nearly zero net current to the probe (because of the high resistance between the probe tip and ground). Since the density of the electrons and ions are nearly equal, and since the electrons move much faster, the floating potential tends to be negative to repel nearly all of the incident electrons.

You should find that the floating potential V_f is negative and relatively small at a pressure of 100-300 mTorr, i.e. between $V_f = 0$ and -10 volts. Now, vary the pressure at a fixed voltage and make a table of the average value of the floating potential vs. pressure. You should see the floating potential drop suddenly (to below –20 volts) above some pressure near 1 Torr. If the floating potential goes lower than –40 volts you will not be able to see it on the scale of this scope, so insert the x10 voltage divider box between the probe and the scope. **If you see any fluctuations or oscillations in the signal, note down the pressure and voltage for future reference (we will return to this in Sec. 9).**

Now vary the high voltage at a fixed pressure, measure the floating potential, and add this to your table of results. You can try this for a few different pressures to see if there is any systematic trend.

Finally, you can try to make a radial profile of the floating potential. Pick a pressure and voltage in the middle of the range that you have explored. Since the probe shaft is grounded, you can just grab the probe shaft while the plasma is on, slightly loosen the nut over the O-ring, gently pull the probe out about 1 cm, and then retighten the nut and clamp. If you see the plasma turn from blue to purple you have let some air into the tube through the O-ring seal. Just wait a minute or two and it should go back to looking as it did before, since there is Helium flowing through the tube. You should see the floating potential drop to near-zero when the probe is far outside the main plasma.

Now make some plots of your data for the floating potential vs. pressure, voltage, and radius. Can you explain any of the variations in these plots (even qualitatively) ? This is not easy without knowing more about the plasma density and temperature, so you can wait until the end of section 8.5 to interpret these results. The main thing to get out of these plots is that you have found the potential at which the electron and ion currents to the probe are equal. What do you think will happen if you make the potential of the probe more positive (or negative) than this ?

8.3 Measurement of Langmuir probe current vs. voltage

In this section you will make the voltage at the probe more positive or negative than the floating potential, and measure the net current to the probe as a function of this voltage. This is a way to estimate the electron or ion density in the plasma. For example, when the probe is positive with respect to the floating potential it will collect mainly electrons, and the rate of electron collection (i.e. the current) should depend linearly on the local electron density.

To do these measurements you will be using a low voltage DC power supply and a sensitive ammeter. The set up is shown in Fig. 8.2. Use only the "300 mA" button to turn the supply on (you will never need over 300 mA). The voltage supply can provide up to 40 volts between the + and – terminals, or ± 40 volts with respect to ground. The setup in the figure puts a + voltage on the tip of the probe, and the current is returned through the ammeter to ground (the probe shaft is also at ground potential). This voltage supply is safe to handle, but don't put your fingers across it.

Before starting to do measurements with the plasma, test the probe driving and measuring circuit by putting a resistor in place of the Langmuir probe. For example, with a 1 kΩ resistor in place of the probe, the current should read -10 mA when the voltage is +10 volts, etc. When you are done with this test, turn the voltage supply knob to zero volts and it turn off the button on the front.

With the high voltage off, put the single-tipped probe you used for Sec. 8.3 near the center of the X2 tube. Now connect the probe to your Langmuir probe circuit using the BNC connector. Now pump down X2 and make a Helium plasma at about 100 mTorr with about 2000 volts on the HV supply. In these conditions the floating potential should be between 0 and -10 volts.

Now turn on the probe voltage supply (300 mA button) and raise the voltage V slowly from 0 to +30 volts DC. You should see the current rise I from near zero to about I=-1 mA (depending on the exact plasma conditions). Keeping the same plasma condition, make a table of the measured probe current vs. the applied probe voltage between 0 and +30 volts in increments of about 5 volts. Repeat once or twice. Then shut the probe voltage supply off and reverse the polarity of the voltage applied to the probe, so that the red lead is now on the "-" terminal instead of the plus, and the "+" terminal goes to the ammeter. Now, measure the current for probe voltages between 0 and –30 volts. Repeat once or twice. You should find that the current is much lower when the voltage on the probe is negative.

Notice that the current changes rapidly with voltage between a few volts negative and a few volts positive. This will be a useful part of the I vs. V "characteristic", so go through this range in very small voltage steps (≈ 1 volt or less) and record I vs. V. To measure voltage with this accuracy you should use a voltmeter and not the scale on the voltage supply (see Fig. 8.2) You now have one Langmuir probe (I,V) curve from which you can evaluate the plasma density and electron temperature. The result should look something like that in Fig. 8.3.

Now you can repeat the same type of probe voltage scan at the same pressure (100 mTorr) but with the high voltage supply at 1000 V and 3000 V instead of 2000 volts. As always, be sure keep the plasma current to ≤10 mA to avoid overheating the high voltage supply. You should find a qualitatively similar curve of probe current vs. voltage at each plasma condition, but the magnitude of the currents should increase to about I = -10 mA at V= +30 volts for the highest plasma voltages.

You can also see what happens to the probe (I,V) curve at a higher pressure up to about 1 Torr, but if you bias the probe to collect electrons at this higher pressure you will probably see the probe tip glow ! This is not due to heating (although this can also occur at high probe currents and voltages), but to excitation of the neutrals by the electrons being drawn to the probe, since they can have a high energy energies and compared with the electrons in the background plasma. Langmuir probe measurements are less reliable in this regime. Also, if the floating potential is below –30 volts (as it can be at high pressure), then when you apply –30 volts to the probe it will now be positive with respect to the floating potential and you will be collecting electrons, not ions ! In this case the limitations of the probe voltage supply will prevent you from making a complete (I,V) curve. In such cases it is better to use the ion saturation current measurements to infer density, since the ion current will not cause local ionization at the probe tip.

You can repeat some of these measurements with Neon if you have time, but the shape of the (I,V) curve should not be qualitatively different.

8.4 Interpretation of the Langmuir probe results

Now that you have a few Langmuir probe (I,V) curves you can try to determine the plasma density and electron temperature. Bear in mind that these are just *estimates* which are likely to be uncertain by at least a factor-of-two, given our oversimplified theory of the probe (see Hutchinson's book or the Supplementary Materials for more details). Also, the theory described below is strictly speaking valid only for *collisionless* plasmas in which the mean free path is large compared to the probe size (see Sec. 8.6.3), which is not necessarily valid in our plasma, especially at high pressures.

Here is the simplest theory. When the probe is biased very positive with respect to the floating potential the tip collects *all* the electrons incident onto it and repels all of the ions incident onto it. This is called the "electron saturation current" region of the probe characteristic. The probe current in this region is therefore:

$$I_e = (1/4)\, n e v_e A$$

where I_e is the electron current to the probe tip, n is the electron (i.e. plasma) density near the tip, v_e is the average electron velocity, and A is the "effective" electron collection area of the probe. The factor (1/4) comes from calculating the flux onto a surface assuming a Maxwellian distribution. For our case A is the area of the probe, since the electric field at the probe surface only extends into the plasma a distance equal to the Debye length, which is much smaller than the probe radius. So if you know v_e from a measurement of the electron temperature, you can infer n from I_e.

The density can also be inferred from the current collected when the probe is biased very negative and is collecting mostly ions, known as the ion saturation current regime. However, for the ion speed you should use the ion acoustic speed $c_s = \mathrm{sqrt}(T_e/m_i)$, since the ions accelerate to this speed in the plasma sheath just outside the probe tip (see textbooks). Thus:

$$I_i = 0.6\, nec_e A$$

Finally, the electron temperature can be inferred from the part of the (I,V) curve in which the probe current rapidly increases, i.e. from just below the floating potential (where the probe current has almost no electron component) to near where the electron current begins to saturate. This latter voltage is called the "plasma potential" V_p (or "space potential"), since it is the potential the plasma would have if the probe was not there. The exact location of the space potential on your curve is hard to determine precisely, but roughly where the slope of the fastest rising part of the curve intersects the slope of the slowly increasing part of the curve, as illustrated in Fig. 8.3.

The simplest way to estimate the electron temperature is realize that in a Maxwellian distribution function at a temperature T_e almost all the electrons have an energy between 0 and $\approx 3\ T_e$. Thus the distance in volts between the floating potential V_f and the space potential V_p is $\approx 3\ T_e$ i.e. over this range in voltage above the floating potential almost all the electrons are collected. For the graph in Fig. 8.3 where $V_f \approx 0$ and $V_p \approx 10$ volts, this implies $T_e \approx 3$ eV (at least, within a factor of two !).

If you want to try a more precise way to estimate T_e you can plot the electron component of the probe current over the range between V_f and V_p and try to fit this curve with an exponential function (i.e. assuming a Maxwellian electron distribution):

$$I = I_i + I_e \exp[e(V-V_p)/T_e]$$

Thus from a log plot of I_e vs. V you can estimate T_e from the slope of the curve (as in the Supplementary Material note from IPP). The fit will not be a pure exponential because the electron distribution function is not purely Maxwellian, but you can estimate T_e and its uncertainty this way.

Now you can use the electron velocity and temperature from a fit to the second equation to infer the density from the electron or ion saturation current equations. Do the densities derived from the electron and ion saturation currents formulas agree with each other ? Don't be surprised if they differ by a factor-of-two; this is normal in Langmuir probe measurements.

8.5 The double probe

While doing the experiment in the previous section you may have wondered whether the probe voltage itself was disturbing the nearby plasma.

Certainly it was when the probe was glowing at high pressure in the electron saturation regime, but how can we be sure the probe current wasn't affecting the plasma at lower pressure ?

One way to help avoid probe perturbations is to use a double Langmuir probe in which there are two nearby tips instead of one (see Fig. 8.1). The double probe is operated by biasing one tip with respect to the other tip, and not with respect to the ground potential, so the pair of probes is always "floating" (i.e. no net current is drawn from the plasma). Thus the local plasma potential is relatively undisturbed by the probe operation. The double probe is also used when there is no convenient ground point in the apparatus, e.g. in RF generated plasmas or spacecraft measurements.

To operate the double probe, hook up the probe to the measuring circuits as shown in Fig. 8.4. Note that there should be no connection to ground in this circuit. At the back of the double probe shaft, the two leads with the blue dots are connected to the tips. Push the probe to near the center of the plasma, and move the single-tip probe to the edge.

Now you can make a plasma as you did in Sec. 8.3 and then vary the voltage between the probe tips in the range –30 volts to + 30 volts. Record the probe current at each voltage. Try switching the leads at the probe to see if the polarity of the bias affects the results. Also try making a double probe curve at other high voltages and pressures, as for Sec. 8.3.

You will notice that the probe currents at ±30 volts are both similar to the ion saturation current for the single probe. Your results should look something like Fig. 8.5. Neither probe can collect electron saturation current because the current into one probe must be equal to the current out of the other probe, and one is always collecting ions, not electrons.

The standard theory for the double Langmuir probe predicts a curve with the shape:

$$I = I_i \tanh(eV/2T_e)$$

where V is the voltage between the probes and I_i is the ion saturation current. Thus you can try to derive the electron temperature from the shape of the curve near V=0. But, as for the single probe, there is some difficulty in defining the ion saturation current since the ion current never really saturates. This is a common problem with Langmuir probes (see Sec. 8.6.2). How does your T_e compare with the results from the single probe ?

8.6 Open Questions and Additional Experiments:

There are many longstanding difficulties and controversies surrounding the interpretation of Langmuir probe measurements in plasmas. Most plasma physicists have given up trying to make absolute and accurate measurements with these probes, particularly in the presence of a magnetic field, and use them mainly for tracking relative behavior. However, in some cases, such as plasma processing of computer chips, there is a strong economic motivation to be as precise as possible. The questions below touch on some of these difficulties, but many of them do not have simple answers.

8.6.1 What determines the floating potential ?

Now that you have a better idea of current vs. voltage characteristics of a probe, can you explain what determines the floating potential you measured in Sec. 8.1 ? Recall that the floating potential is different from the plasma potential by about $3T_e$, so what you need to do is explain the plasma potential. How should it vary with the high voltage applied ? Why does it go very negative at high pressure ?

8.6.2 Probe saturation current

Clearly the current to the probe does not "saturate" at voltages well above the electron temperature in either in the ion or the electron direction. Evidently the probe can collect more charge than expected from the simple theory at higher voltage. Looking at the equation for the saturation current you may suspect that this is due to an increasing "effective" area of the probe at high voltage voltage. Why would this happen ? It is also possible that the electron distribution function is non-Maxwellian, i.e. that part of the slow increase in I_e is real. How could you tell ?

8.6.3 Collisional and Debye effects

Two of the assumptions in the simple theory of the single or double probe are that the Debye shielding distance is smaller than the size of the probe, and that the ions and electrons have a mean free path longer than the Debye length of the plasma near the probe. Check these assumptions by plugging in the plasma parameters for your measurements, including the neutral density from the pressure measurement. Is the probe in the collisionless regime ? If not, how do you expect the probe (I,V) curve to change ?

8.6.4 Probe perturbation effects

You may have wondered whether the presence of the probe tip or insulating probe shaft affects the plasmas, even if the probe was floating. This is often an important practical question in the use of Langmuir probes, but there is no simple general answer: it should be checked for each case. So try to check the effect of one of these probes on the measurements of the other by moving them close together and then far apart. For example, you can measure the floating potential on the single probe when moving the double probe in and out (avoid touching one probe with the other).

8.6.5 Probe current vs. plasma current

At some point in this experiment you may have become confused about the relationship between the Langmuir probe current and the total plasma current between the main electrodes, since both could be in the range 1-10 mA. Is there a good reason for this similarity in the two currents ? Can the two main electrodes be considered as a large Langmuir probe ? If so, why isn't the current much larger since the area of the electrode is much larger and the voltage between the electrodes is much larger ?

8.6.6 Magnetic field effects on the probe

You can try to see the effect of a magnetic field on the probe by moving the permanent magnet near to and far from the probe tip. How can you tell whether the magnetic field is affecting just the probe charge collection process, or rather the plasma near the probe ?

References:

Hutchinson, Principles of Plasma Diagnostics (2nd Ed. 2002) Ch. 3

Huddlestone and Leonard, Plasma Diagnostic Techniques (1965)

Supplementary Materials:

Demidov et al, Electric probes…, Rev. Sci. Inst. 73, p. 3409 (2002)

http://www.ipp.mpg.de/de/for/bereiche/diagnostik/psi/equipment/sonden.html

www.ee.ucla.edu/~ffchen/Publs/Chen210R.pdf

Sec. 9: Plasma instability

9.1 Introduction:

This experiment is more like an open-ended research project: you will make measurements of a plasma instability in X2 and try to understand what causes it. This will help you to develop some plasma diagnostic techniques and perhaps some familiarity with plasma instability theory. You can find papers about similar instabilities in the Supplementary Materials.

9.2 Finding the instability:

The simplest way to find the instability is to go back to the single-probe floating potential measurement of Sec. 8.2 and repeat that procedure. Start with Helium first and retract the double probe to outside the plasma before you proceed. When you raise the pressure to about 1-2 Torr you should begin to see an oscillation in the floating probe signal on the oscilloscope. It should have a frequency of about 10 kHz and an amplitude of about a volt (these numbers can vary by at least a factor of two depending on the exact pressure and high voltage).

Now, try to trigger the scope on the incoming floating probe signal so you can see the time dependence of the signal over a few cycles. In some regions of pressure the instability is almost sinusoidal, while in others it has a "sawtooth" shape or has a multiple frequency structure. Typical waveforms are illustrated in Fig. 9.1. This type of complexity is normal for plasma instabilities.

Before you go on, you should think about whether the finite frequency response of the floating probe circuit is affecting what you see. The probe itself will have some capacitance C and the scope has an input resistance of about R=1 MΩ; thus there is some frequency f=1/RC above which the circuit does not respond to the voltage at the probe tip. What is this frequency ? Ideally, you should take out the probe and put a test signal at the tip to determine this, but you can mock up the probe with a simple wire and use the signal generator for a test signal.

At this point you can do one of several things: determine the "parameter space" in which the instability can be found in this device, make more detailed measurements at one set of parameters, look in the Supplementary Materials (or elsewhere) for previous papers about this instability to guide your experiments, or try to figure out for yourself what is happening. The order in which you do these is not so important.

9.3 Survey of parameter space:

The experimentalist's approach to a understanding an instability is to first survey the available parameter space in order to find out where and when this instability occurs. In X2 you have three parameters which you can vary: the type of gas, the gas pressure, and the high voltage. At this point you have only a few plasma measurements to make at each point in this space: the floating potential and its fluctuations, the plasma current, and the visual appearance of the plasma. In Sec. 9.5 you will make more detailed measurements.

Keep the floating probe near the center of the discharge and vary each of these parameters over the available range, as time permits. Make a table showing when you see the instability in the floating probe, its rough characteristics (amplitude, frequency, complexity), and also the plasma current and the visual appearance of the plasma. When you're done, make a few graphs showing the parameter space over which you see the instability.

9.4 Need for more information:

If you are a clever plasma theorist you might attempt to understand this instability with just the information available from Sec. 9.3. However, it usually helps to have more information before you begin to try to understand something complicated like this.

What type of additional information would you like to have in order to understand the physics of this instability ? Of course, it is difficult to be sure until you have a specific theoretical model you would like to test. But some useful things to know would be:

a) spatial structure: Where is the fluctuation level the largest ? Are all parts of the plasma fluctuating in phase, or is the instability moving through the plasma ? What is the radial structure of the fluctuation level ?

b) plasma fluctuations: How big are the fluctuations in the electron density and/or temperature ? Is the plasma current fluctuating also ? Is the light emission fluctuating ?

c) time evolution: It would be useful to measure the time development of the instability as it first appears, since this relates to its linear growth phase rather than to its nonlinearly saturated (steady-state) phase. However, in this and many other cases the linearly growing phase is difficult to measure since it is so transient, and we are left with the nonlinear state which is more difficult to understand, since it must also depend also on the process which stop the instability growth.

9.5 Additional measurements:

Look at the list of Sec. 9.4 and see if you can measure any of the things using the diagnostic techniques you have tried so far.

a) floating potential profile: The only measurement you can make without new diagnostics is the radial profile of the floating potential fluctuation level. Pick a condition in which the instability is clear and relatively far from the boundaries of its location in parameter space (to minimize the effect of the probe on the instability). Then measure the amplitude and frequency of the floating potential fluctuations as a function of the radial position of the probe, and graph the result. Is this instability localized near the center or the edge, or is it occurring over the whole radial profile ?

b) density fluctuation measurements: With a slight modification to the Langmuir probe circuit of Sec. 8.3 you can measure the plasma density fluctuations with a single probe. The modification is to add a series resistor in the circuit between the ammeter and the ground, as shown in Fig. 9.2. The voltage across this resistor is proportional to the current I through the probe circuit. It is important to put the resistor at this location so that the signal is at ground potential on one side of the resistor, so it can be connected to the ground of the scope. Choose the resistor value so that IR is about 1 volt, e.g. for electron saturation current $I \approx 1$ mA and so $R \approx 1000\ \Omega$, and for ion saturation current $I \approx 10\ \mu$A and $R \approx 100$ kΩ. Check to see what happens as you vary the voltage on the probe; this should not change the instability, but if it does you are perturbing the plasma with the probe ! If so, reduce the probe current by using the ion saturation signal rather than the electron saturation signal. What is the relative fluctuation level of the plasma density ? How big is this compared with the relative fluctuation level of the floating potential ? Can you tell if there are electron temperature fluctuations ?

c) capacitive probe measurements: A simple way to measure the instability is to measure the voltage "picked up" by an electrode just outside the glass tube of the plasma, as shown in Fig. 9.3. The electrode becomes one plate of a capacitor, the other plate of which is the plasma itself, so the voltage on the electrode follows the voltage at the surface of the plasma. The electrode can be a piece of aluminum foil or any conductor. This electrode can be connected to the scope with a BNC cable, and the fluctuations should be easily visible at the volt level. How large are the capacitive probe voltage fluctuations compared with the floating probe fluctuations ? Can you see any phase difference between the two ? You can try to put two capacitive probes at the same time into two of the five holes at the back of X2 to see if you can measure any phase difference in the fluctuations along the height of the column.

d) silicon photodiode measurements: Another simple way to measure the instability is by measuring the fluctuations in the light emission from the plasma. The lab comes with two photodiodes from Edmund Scientific (part 53-378). First, read about these devices in the "Edmund Optics – Silicon Detectors" file in the Supplementary Materials. Then test their operation using room light, and also using a pulsed LED (to check the frequency response). Now try to measure the light from the plasma, and look for fluctuations in this light at the frequency of the floating probe fluctuations (use both beams of the scope). The diodes can be plugged directly into the holes at the back holes of X2 using the small black plastic tube, or connected to X2 via plastic fiberoptic cable, also supplied. Check whether the signals you see are really do to light by blocking and unblocking the photodiode – you may have strong electrical 'pickup' from the diode itself (acting like a capacitive probe) ! You need to electrically shield the diode, and maybe also use the plastic fiberoptics to move the diode far from the plasma. Can you measure the phase of the light fluctuations with respect to those in the floating potential ? Can you use two diodes to measure the spatial structure of the fluctuations along the tube ?

e) current fluctuation measurement: You might be wondering if the plasma current as a whole is fluctuating during this instability. You can try to measure the current fluctuation using a magnetic pickup loop, similar to the one you used to measure the strength of the permanent magnet. First, estimate what level of magnetic field fluctuations you might expect if the plasma current were 10% fluctuating (i.e. by about 1 mA), and then estimate the induced voltage in a loop of wire with an area of about 30 cm^2 given a typical fluctuation frequency. Then try to measure the current fluctuation and determine the actual % fluctuation level in it. This might tell you something important about the mechanism of the instability.

9.6 Interpretation of this instability:

Your challenge now is to understand what causes this instability. Here are some suggestions:

a) Look at the papers in the Supplementary Materials section for related work, but do not assume that you have exactly the same instability that they are talking about ! Try to find the reference which has the most similar situation, i.e. similar pressure, gas species, and tube geometry. You can look on Google or search a database of scientific journals.

b) Once you have an idea for a physical mechanism which causes the instability, try to think of experimental tests of this idea. For example, if the instability involves ionization waves (a common theme in the literature of similar experiments), you might try to measure the phase between the light fluctuations and the plasma density fluctuations.

c) Try new things to see their effect. For example, how does the instability react to the presence of a magnetic field (from the permanent magnet), or to the presence of electrical conductors outside the glass tube ?

References:

Fridman and Kennedy, Plasma Physics and Engineering, Sec. 6.3 and 7.4

Sec. 10: Launching waves

10.1 Introduction:

Many types of waves can be created in a plasma using controlled energy from the outside, in contrast to the uncontrolled waves associated with internal instabilities. Such externally driven waves can be used to create plasmas, to heat plasmas, to drive current in plasmas, to separate different ion species within the plasma, to measure the properties of plasmas, etc. In this experiment you will try to launch such a wave and to measure its properties. As in Sec. 9, this is an open-ended experiment which will challenge your ability to measure and understand what's happening in the plasma.

10.2 Types of Plasma Waves:

There are many books and papers on plasma waves, a few of which are listed in the References. However, there are only a few basic types of plasma waves: electromagnetic waves (analogous to light wave), electron plasma waves (fast electron oscillations), ion acoustic waves (slower ion oscillations), and Alfven waves (magnetic field oscillations).

The simplest wave which can be launched in a plasma like ours is an ion acoustic wave, which is analogous to a sound wave in air. The main thing which fluctuates is the ion density, which also causes the electron density and plasma potential to fluctuate in response to the ion fluctuation (the plasma is always approximately neutral).

The propagation speed of an ion acoustic wave is c_s (sub-s for sound):

$$c_s = \mathrm{sqrt}(T_e/m_i)$$

This hold for relatively long wavelength waves with $k\lambda_D << 1$ and for cold ions ($T_i << T_e$), where $k=1/\lambda$ (the wavelength of the wave), and λ_D is the Debye length. In this experiment you control the wave frequency with the signal generator outside the plasma, so the wavelength of the ion acoustic wave is:

$$\lambda = c_s/f$$

For example, if T_e = 1 eV and m_i = 20 (Neon), then if f=100 kHz what is λ ? (you can use the NRL plasma formulary to help evaluate c_s). Evaluate λ_D to see if $k\lambda_D << 1$.

Ion acoustic waves can be driven by local fluctuations in the ion density or electrostatic potential (since the ions will respond to changes in the potential). Ion acoustic waves can be damped by collisions with neutrals, so the experiment is best done at low pressure. Ion acoustic waves can also be damped by ion Landau damping, but only when $T_i \approx T_e$, which is not the case in this experiment where $T_i << T_e$.

10.3 Launching and detecting the wave:

Plasma waves are usually launched with a “mesh” probe like that shown in Fig. 10.1. The plasma partially flows through the mesh and presumably makes better contact with the plasma this way. However, the details of the wave launching process are complicated and not necessarily well understood.

Insert the mesh probe in the left port of X2, with the single or double Langmuir probe on the right port. Start with the mesh just inside the inner wall of the tube, and the Langmuir probe tip about 1 cm inside the inner wall of the tube. Connect the Langmuir probe to the scope to measure floating potential (as in Sec. 8). Connect the mesh probe to the signal generator as shown in Fig. 10.2, so that the mesh is biased with a positive-going sine wave of amplitude about 5 volts and a frequency of 100 kHz. Also connect the signal generator to the scope to use as a reference.

Now, make a Neon plasma in X2 with a supply voltage of 1000 VDC, and reduce the pressure to a minimum by nearly closing the needle valve. The pressure should be about 60 mTorr. You should see a sine wave on the Langmuir probe floating potential at the same frequency as the signal generator. Vary the frequency and amplitude of the input to confirm that the floating probe signal is due to the signal generator. You have created a and detected a plasma wave !

10.4 Properties of the wave

Now you can measure the properties of this wave with all the plasma "knobs" and diagnostics you have used so far. The goal is to characterize the wavelength and amplitude of the wave under various conditions, so that you can compare the results to the simple ion acoustic wave theory of Sec. 10.2. But do not assume that this is an ion acoustic wave ! You should always be alert for the presence of electromagnetic "pickup" or some other spurious signal.

The main things you can measure with the floating probe are the received wave amplitude and the time delay between the launched and received wave (as seen on the scope). The time delay will tell you the wave speed if you know the distance between the launcher and receiver. Look back at the expected behavior of ion acoustic waves in Sec. 10.2 for guidance about what to vary. Also look for any distortions of the waveform, which would indicate some nonlinear effect in the wave propagation. Here are some "knobs" you can try:

a) vary the frequency, amplitude, and polarity of the driving signal
b) vary the gas pressure and/or plasma current (i.e. high voltage)
c) vary the position of the wave launcher and/or Langmuir probe
d) vary the gas species (can try air, too)
e) vary the magnetic field (with the permanent magnet)

You can also try different diagnostics:

a) measure the density fluctuations with a biased probe

b) measure the potential fluctuations with a capacitive probe

c) look for visible light fluctuations with the photodiode

d) increase the distance over which the wave can propagate by modifying the mesh or Langmuir probe to extend down towards the ground electrode (not the high voltage electrode on top !),

10.5 Identification of the wave

Now you should have enough information to determine whether what you have measured is an ion acoustic wave. Is the propagation speed the ion acoustic speed ? If not, why not ? If not, what type of wave is this ? If you can answer this question you should write a paper about it !

11. More Experiments

There are many more plasma experiments which can be done with this laboratory. Below are a few suggestions, to go along with some references in the Supplementary Materials. Two things to keep in mind:

a) SAFETY FIRST ! Many of the experiments below involve hazards which are not discussed in this manual; for example, those associated with RF power. Always check with your college safety office before trying to do anything new with this laboratory.

b) Avoid making irreversible changes to the existing equipment ! If you want to make changes be sure you can return the equipment to its original state so that other students can do the experiments described in this manual.

11.1 Effect of the electrode on breakdown and plasma structure:

You can unscrew the top (cathode) electrode on X2 and replace it with anything you like; for example, a pointed cathode or a spherical cathode. Does the breakdown voltage depend on the size or shape of the cathode ? Does the discharge structure change ? Why ? You can also replace the anode but you have to take the plastic and glass tube off first.

11.2 Effect of a hot filament on the plasma:

A supplementary source of electrons can be created in X2 by inserting an electron-emitting filament through one of the side ports and heating it. You might be able to attach a small light bulb filament to the tip of one of the probe, and heat it with a flashlight battery. Do the electrons affect DC breakdown ? Are you sure it's the electrons and not the UV light emitted by the filament ? How does the filament affect the plasma ?

11.3 Electron beam generated plasma:

In X2 it is difficult to make a plasma at low pressure (< 50 mTorr), probably because the plasma loss is too great to sustain a current from secondary electron emission on the cathode. Can you create a plasma with an electron beam created by the filament of 11. 2 ? You may have to bias the filament above 25 volts to create ionization. Are there any instabilities generated by the electron beam-plasma interaction ?

11.4 AC generated plasma:

You can probably find at the hardware store a battery operated fluorescent light bulb. Can you use the power supply of that bulb to make a plasma in X2 ? First measure the voltage waveform on the scope. Be careful since there is probably high voltage generated by the supply. You can also try using a neon sign transformer, but this is considerably more dangerous due to the higher power level.

11.5 RF generated plasma:

If you have access to an RF source with a few watts of power somewhere in the frequency range 100 kHz – 10 MHz, you can try to create a plasma in X2 using either inductive coupling (coils around the glass tube) or capacitive coupling (metal electrodes near the tube). RF generated plasmas are used for plasma processing of computer chips and many other practical applications. You might be able to buy a surplus RF power supply for experiments. Be aware that there are regulations concerning RF power generation since it can interfere with radio communications.

11.6 Microwave generated plasma:

If you have access to a low-power microwave generator you can try to make a microwave-generated plasma in X2. You can investigate the coupling of microwave energy to the electrons at their cyclotron resonance (see paper by Orr and Wilson). You can also get a large amount of microwave power at 2.45 GHz from microwave oven, and there are many web sites which tell you how to make plasmas inside the oven. Do not try to disassemble the microwave oven without expert technical support since both the power supply and the microwaves themselves can be dangerous.

11.7 Magnetic confinement:

You have seen in Sec. 5 how a single permanent magnetic can strongly affect the plasma structure. Now you can try to improve the plasma confinement in X1 or X2 by surrounding the tube with multiple permanent magnets in a magnetic cusp configuration (see Plasma Sources or Magnetic Mulitpoles paper). Can make a plasma at lower gas pressures using this technique ? This method is often used with hot electron emitting filaments to create a quiet plasma for lab experiments.

11.8 Time dependence of plasma breakdown:

You can use the floating Langmuir probe and scope to investigate the time dependence of the plasma breakdown process. Just repeat the Paschen curve experiment in X2 and trigger the scope to record the breakdown (you will need to use the "storage" mode of the scope or record the scope trace with a camera). See the paper on Ionization Cascade.

11.9 Chaos:

If you have access to a spectrum analyzer you can observe the development of "chaos" during the instability described in Sec. 9. Simply put the floating probe signal into the spectrum analyzer and observe the development of the frequency spectrum as a function of the gas pressure. You may see the famous "period-doubling' route to chaos, or the "spatiotemporal irregularity" described in the paper by Dinklage (Sec. 9).