Experimental Plasma Station for the undergraduate curriculum

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Abstract

Plasmas are a type of an ionized gas that constitutes the fourth and most common naturally occurring state of matter in the visible universe. Despite providing a wealth of applications from all areas of classical physics, playing an important role in many industrial applications and the likelihood that plasmas will play a key role in the world's future energy portfolio, plasma physics does not often appear in the undergraduate curriculum. This is particularly true in the laboratory setting, where most experiments involving plasmas require the use of fairly complicated and complex experimental setups. In this poster, we present the design of a relatively simple and inexpensive experimental setup that supports a number of experiments that use plasmas as an experimental medium to explore many areas of classical physics and can be used throughout the physics undergraduate curriculum. The apparatus is designed to be easy to implement and can be replicated at many institutions, regardless of the presence of local expertise. We will also present three experiments that can be performed in both the intermediate and advanced laboratory, including plasma spectroscopy, electrical breakdown of a gas into a plasma (Paschen's Law), and measurement of electron temperature and density using a simple probe.

Motivation

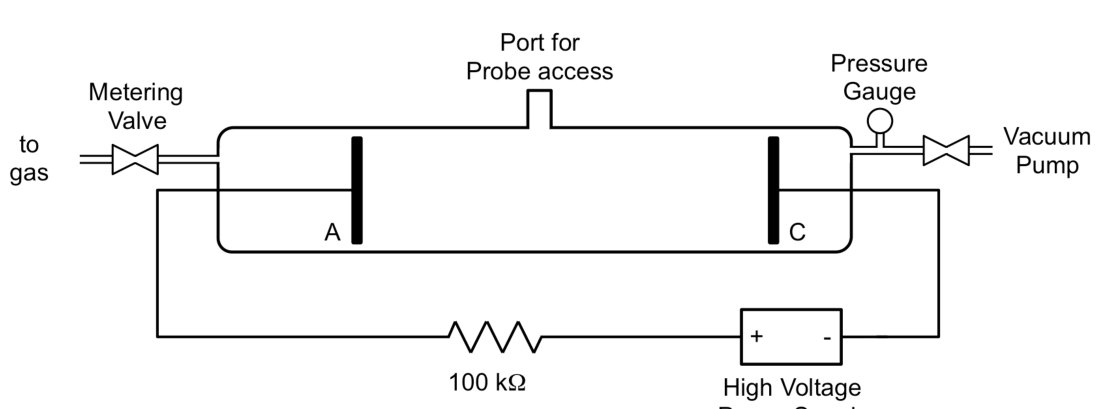
- Plasmas are a unique and intriguing state of matter that present many opportunities for labs beyond the first year.
  - Complex system that provides opportunities for experiments covering the breadth of classical physics that can be fairly narrow to open ended.
  - Applications of plasmas span from purely scientific to industrial, making them appealing to a wide variety of students.

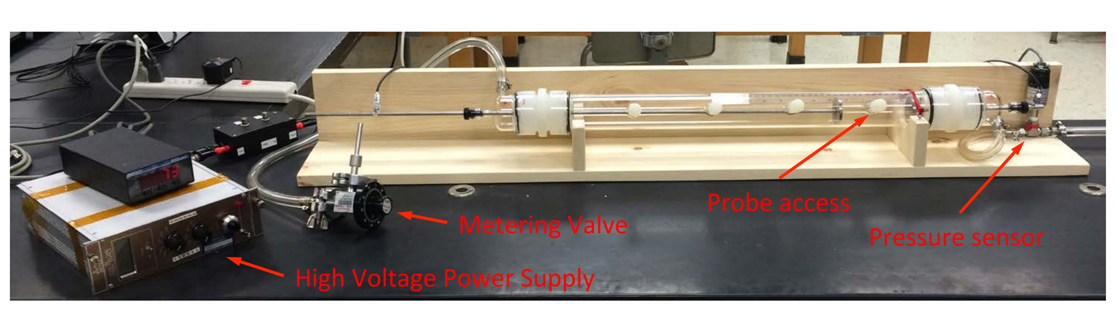
Design constraints

- Develop a simple and robust experimental station that provides a wide breadth of experimental opportunities. It should
  - be accessible at places with minimal or no technical support
  - have a standard design that uses as many off the shelf components and require as little custom machining as possible.
  - support many experiments that can be done in labs beyond the first year to bring the cost per experiment to a modest level

Design

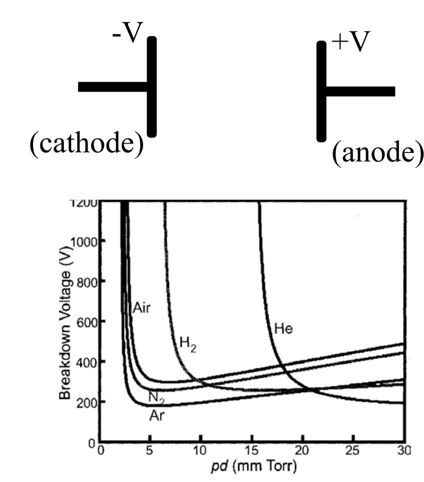
- A DC glow discharge is used as the plasma source
  - High Voltage power supply (~500V)
- Operates under medium vacuum (10 – 1000 mTorr)
  - Roughing pump with thermocouple/convectron vacuum gauge
  - Gas feed system allows for a variety of working gases
  - Could easily be extended to higher vacuum with better pumps
- Chamber is made from pyrex glass to provide optical access

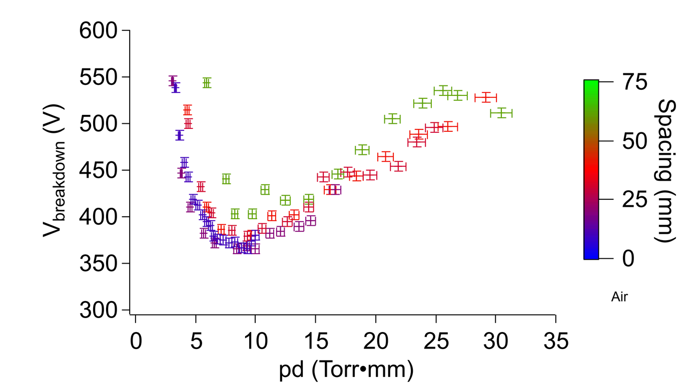


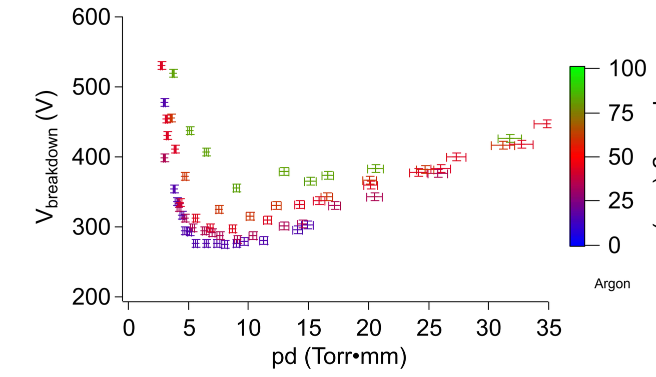


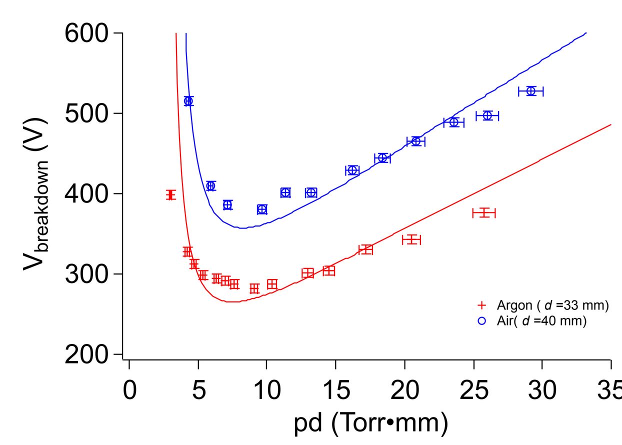
Paschen's Law

- Examine the phase transition from gas to a plasma by biasing parallel electrodes with a dc voltage.
- As the voltage difference is applied, free charges are accelerated by the resulting electric field.
- If an electron acquires more than the ionizing energy of the gas, the electron can ionize the neutral particle and create a new free electron and a free ion.
- The free ion is then accelerated toward the cathode. When it hits the cathode, it can free an electron from the cathode (secondary emission).
- The electrons created by the secondary emission are what sustain the plasma.
- The voltage necessary for this exceed this threshold to sustain the plasma is known as the breakdown voltage, $V_{breakdown}$, depends on electrode spacing, d, and neutral gas pressure, p.
  - The optimal condition for breakdown occur at the minimum of a Paschen curve, a plot of V vs. pd.









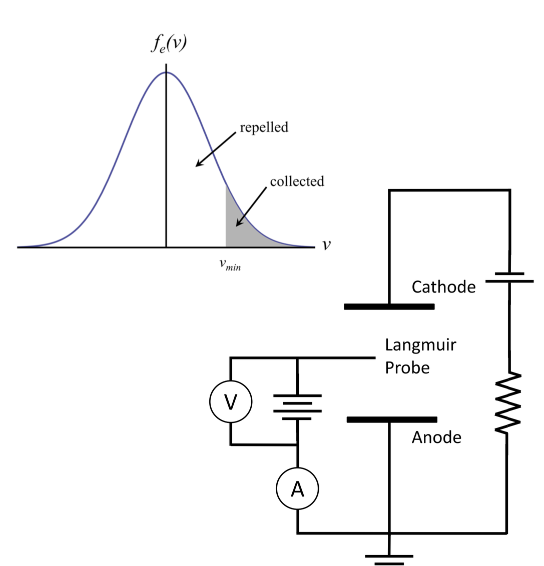
- The exact shape of the curve depends on the materials and shape of the electrodes and the working gas.

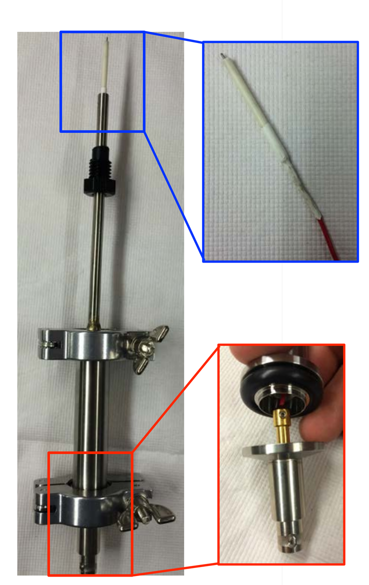
$$V_{breakdown} = \frac{B\,(pd)}{C + \ln{(pd)}}$$

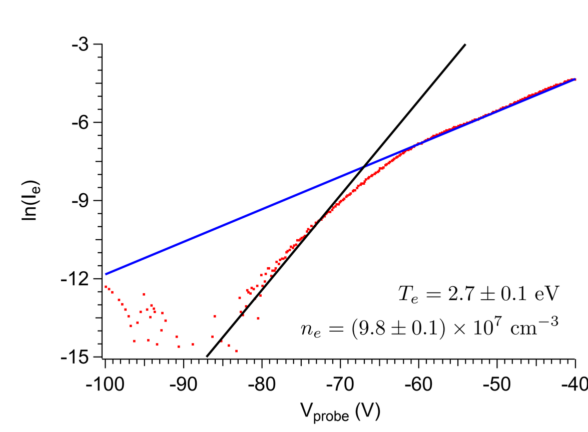
where $C = ln(A) - ln\left(1 + \frac{1}{\gamma}\right), B = AU_i\ , A = \frac{\sigma_n}{k_B T_n}$, γ is the secondary electron emission coefficient, U_i is the ionization energy of the gas, σ_n is the electron-neutral collision cross section and T_n is the temperature of the neutral gas.

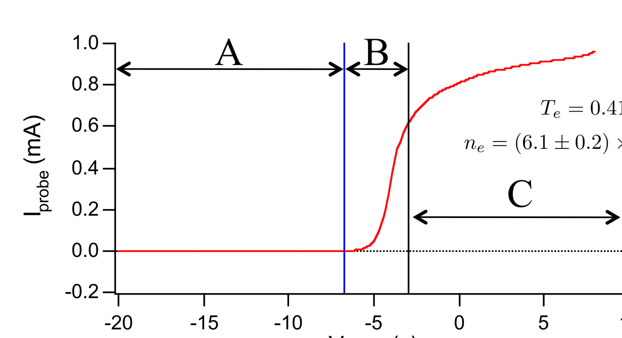
Probe Measurements to measure the electron distribution functions, temperature and density

- Bias a small conducting probe in the plasma and measure the current that is collected by the probe.
- By varying the probe voltage, you measure parts of the ion and electron distribution functions





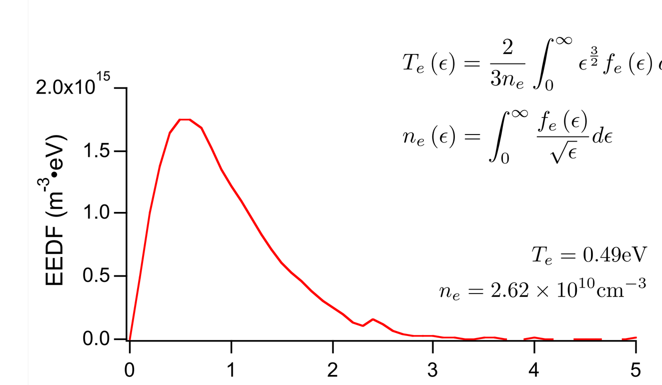




A: All electrons are repelled but the ion population is measured

B: Measure an increasing fraction of the electron population and the entire ion population

C: Local plasma is depleted and the entire electron distribution is measured.

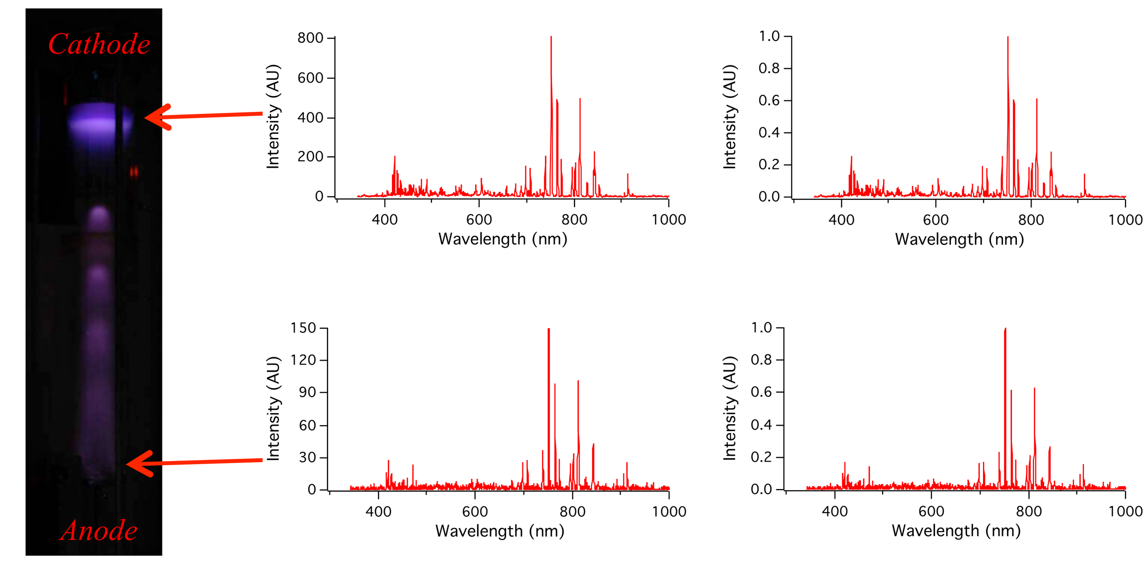


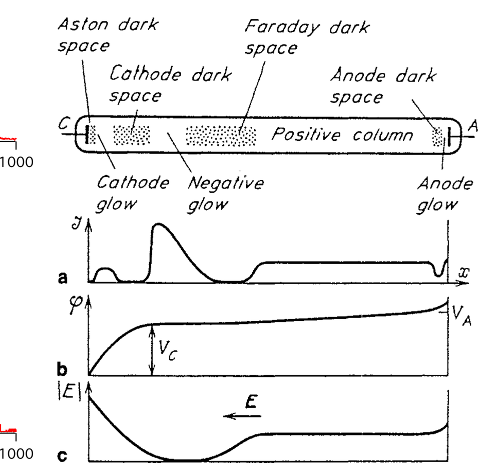
The EEDF can be reconstructed from the electron current using the Druyvesteyn method.

$$f_e(\epsilon) = \frac{2}{A_{probe} q_e}\sqrt{\frac{2m_e\epsilon}{q_e}}\frac{\partial^2 I_e}{\partial V_{probe}^2}$$

Spectroscopy

- Plasmas provide a natural system for examining atomic transitions.
  - The observed emission spectra depend on the electron temperature, which can vary throughout the discharge.

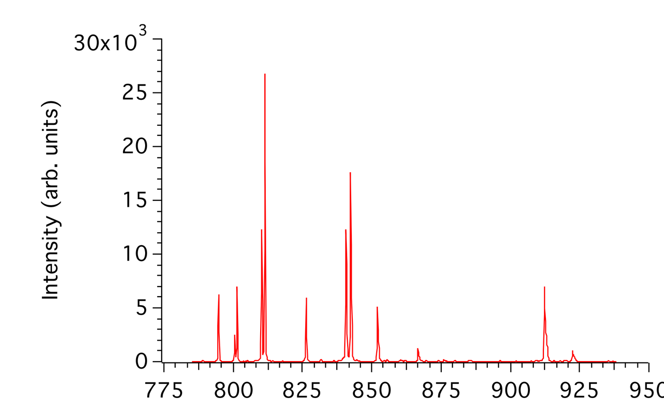


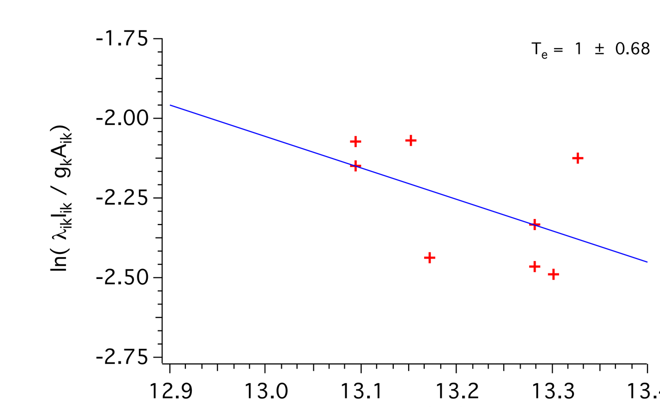


- The intensity of the spectral line due to the transition from energy level k to i, I_{ik}, is proportional to $\frac{hcA_{ki}n_k}{4\pi\lambda_{ki}}$ where λ_{ki} is the observed wavelength, A_{ki} is the transition probability for spontaneous emission, and n_k is the population of the excited states.
- Assuming that the the system is in thermal equilibrium, it can be described by the Maxwell-Boltzmann distribution and the population of the excited states, n_k, will depend on the Boltzmann factor e^{-E_k/k_BT_e} and the quantum degeneracy factor g_k. Using this, we can find the temperature of the plasma relative intensities of the different spectral lines.

Observed Wavelength (nm)	g_kA_{ki} (s^{-1})	E_k (eV)	Lower Level Conf., Term, J	Upper Level Conf., Term, J
794.8176	5.58e+07	13.28263821	$3s^23p^5(^2P°_{1/2})4s\ \ ^2[^1/_2]°$	$3s^23p^5(^2P°_{1/2})4p\ \ ^2[^3/_2]$
800.6157	2.45e+07	13.17177690	$3s^23p^5(^2P°_{3/2})4s\ \ ^2[^3/_2]°$	$3s^23p^5(^2P°_{3/2})4p\ \ ^2[^3/_2]$
801.4786	4.64e+07	13.09487176	$3s^23p^5(^2P°_{3/2})4s\ \ ^2[^3/_2]°$	$3s^23p^5(^2P°_{3/2})4p\ \ ^2[^5/_2]$
810.3693	7.5e+07	13.15314307	$3s^23p^5(^2P°_{3/2})4s\ \ ^2[^3/_2]°$	$3s^23p^5(^2P°_{3/2})4p\ \ ^2[^3/_2]$
811.5311	2.32e+08	13.07571492	$3s^23p^5(^2P°_{3/2})4s\ \ ^2[^3/_2]°$	$3s^23p^5(^2P°_{3/2})4p\ \ ^2[^5/_2]$
826.4522	4.59e+07	13.32785623	$3s^23p^5(^2P°_{1/2})4s\ \ ^2[^1/_2]°$	$3s^23p^5(^2P°_{1/2})4p\ \ ^2[^1/_2]$
840.8210	1.12e+08	13.30222666	$3s^23p^5(^2P°_{1/2})4s\ \ ^2[^1/_2]°$	$3s^23p^5(^2P°_{1/2})4p\ \ ^2[^3/_2]$
842.4648	1.08e+08	13.09487176	$3s^23p^5(^2P°_{3/2})4s\ \ ^2[^3/_2]°$	$3s^23p^5(^2P°_{3/2})4p\ \ ^2[^5/_2]$
852.1442	4.17e+07	13.28263821	$3s^23p^5(^2P°_{1/2})4s\ \ ^2[^1/_2]°$	$3s^23p^5(^2P°_{1/2})4p\ \ ^2[^3/_2]$

$$\ln\left(\frac{\lambda_{ik}I_{ik}}{g_kA_{ik}}\right) = -\frac{E_k}{k_BT_e} + C$$





Summary

- Plasmas are the most common form of matter in the visible universe and have many technological applications.
- Plasmas can provide a unique experimental environment for the advanced laboratory.
  - They can be used to demonstrate many ideas from across the spectrum of classical physics and can be revisited many times throughout the undergraduate curriculum.
  - They are a highly nonlinear system
- This poster presented a simple, low-cost experimental system that allows one to examine a wide range of physics through a number of open ended experiments.

Useful References

- Stephanie A. Wissel, Andrew Zwicker, Jerry Ross and Sophia Gershman, *The use of dc glow discharges as undergraduate educational tools*, Am. J. Phys., **81**, 663 (2013).
- These experiments have been offered as part of an ALPhA Immersion. Additional details can be found on the wikis that were created for these immersions.
  - Paschen's Law http://www.compadre.org/advlabs/wiki/Plasma_Physics:_Electrical_Breakdown
  - Plasma Probes http://www.compadre.org/advlabs/wiki/Plasma_Physics:_Plasma_Probes
  - Spectroscopy http://www.compadre.org/advlabs/wiki/Plasma_Physics:_Plasma_Probes

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