The Plasma Experiment – Lennon O Naraigh (JSTP)

Date

Abstract:

This experiment consists of two parts. In the first part, the *I-V* characteristic of a flow of electrons in an argon-filled tube (884) is studied and consequently the charge-to-mass ratio of the electron is obtainable, and is found to be the following:

$$\frac{q}{m} = \ldots$$

(where we have adopted Feynmann's convention that q denotes a charge in S.I units).

In the second part, another argon-filled tube (Z300T) is used to study the electron density and electron temperature of the ionized argon, using a Langmuir probe. In this experiment, the following results were obtained for the electron density and temperature respectively:

$$n_e = \ldots$$
$$T_e = \ldots$$

Basic Theory and Equations:

The Child-Langmuir law gives the current density as a function of voltage for a beam of thermal electrons in transit through a container or tube. In one dimension, the analysis proceeds as follows:

Consider the case of two infinitely long parallel plates A & B. Assume that plate A emits electrons through thermionic emission. Let the other plate, B, be positively charged. Given this charge on plate B, there is a potential difference $V(x)$ across the plates. We have a flow of electrons (current), and an applied potential, and seek therefore to derive the *I-V* characteristic.

Assuming that the emitted electrons have low velocities, and that the potential at the plate A is zero, then the electron velocity at arbitrary time is v, given by

$$qV = \frac{1}{2}mv^2 \tag{1}$$

Poisson's equation in one dimension is,

$$\frac{d^2V}{dx^2} = \frac{\rho}{\varepsilon_0} \tag{2}$$

Further, the current density is given by

$$J = \rho v \tag{3}$$

Combining these equations gives the following differential equation for V:

$$\frac{d^2V}{dx^2} = \frac{1}{\sqrt{V}} \frac{J}{\varepsilon_0} \sqrt{\frac{m}{2q}} \tag{4}$$

Multiplying up by the integrating factor $2\frac{dV}{dx}$ enables us to find a solution to (4). Assuming that $\frac{dV}{dx}\big|_{x=0} = 0$, we get the following equation for J as a function of V:

$$J = \frac{4\varepsilon_0}{9} \sqrt{\frac{2q}{m}} \frac{V^{\frac{3}{2}}}{x^2} \tag{5}$$

This is the simplest instance of the Child-Langmuir Law. The $V^{\frac{3}{2}}$-dependence is characteristic of this law.

Now the argon tube is cylindrically symmetric, and Poisson's equation, for this situation is the following:

$$\left(\frac{1}{r}\frac{d}{dr} r \frac{d}{dr}\right) V = \frac{\rho}{\varepsilon_0} \tag{6}$$

Again, from cylindrical symmetry,

$$J = 2\pi r v \rho \tag{7}$$

Combining equations (6) and (7) with equation (1) gives

$$r\frac{d^2V}{dr^2} + \frac{dV}{dr} = \frac{J}{2\pi\varepsilon_0} \sqrt{\frac{2m}{qV}} \tag{8}$$

Langmuir[1] solves this equation and his solution, for this cylindrically symmetric situation, implies the following the current-voltage relation:

$$I = 2\pi\varepsilon_0 \left(\frac{4L}{9R}\right) \sqrt{\frac{2q}{m}} V^{\frac{3}{2}} \tag{9}$$

At higher voltages the assumption of non-interaction between the gas in the tube and the electrons fails, and the electrons interact with the argon to ionize the latter. The voltage at which this occurs is a measure of the ionization potential of argon.

In the second experiment, the plasma is initially ionized, and the behaviour of the electrons therein is examined. This behaviour relies on the notion of a *sheath*.

Consider a plasma confined in the one-dimensional trap outlined above. Electrons and ions can hit the plates (the wall) and when they do, they recombine and are lost. Now the electrons, having much higher thermal velocities than the more massive ions, are lost faster. Thus, the plasma has a potential positive with respect to the wall. This potential is distributed in a finite layer about the walls, and exists on all cold walls with which the plasma is in contact. This is the *sheath*.

The relevant equations in this section come from the fact that the electrons have a Maxwellian velocity distribution, whence

$$I \propto \exp\left(\frac{qV}{k_B T_e}\right)$$

(10)

Where T_e is the electron temperature.

Further, at higher voltages, the current I saturates, and this occurs at a value

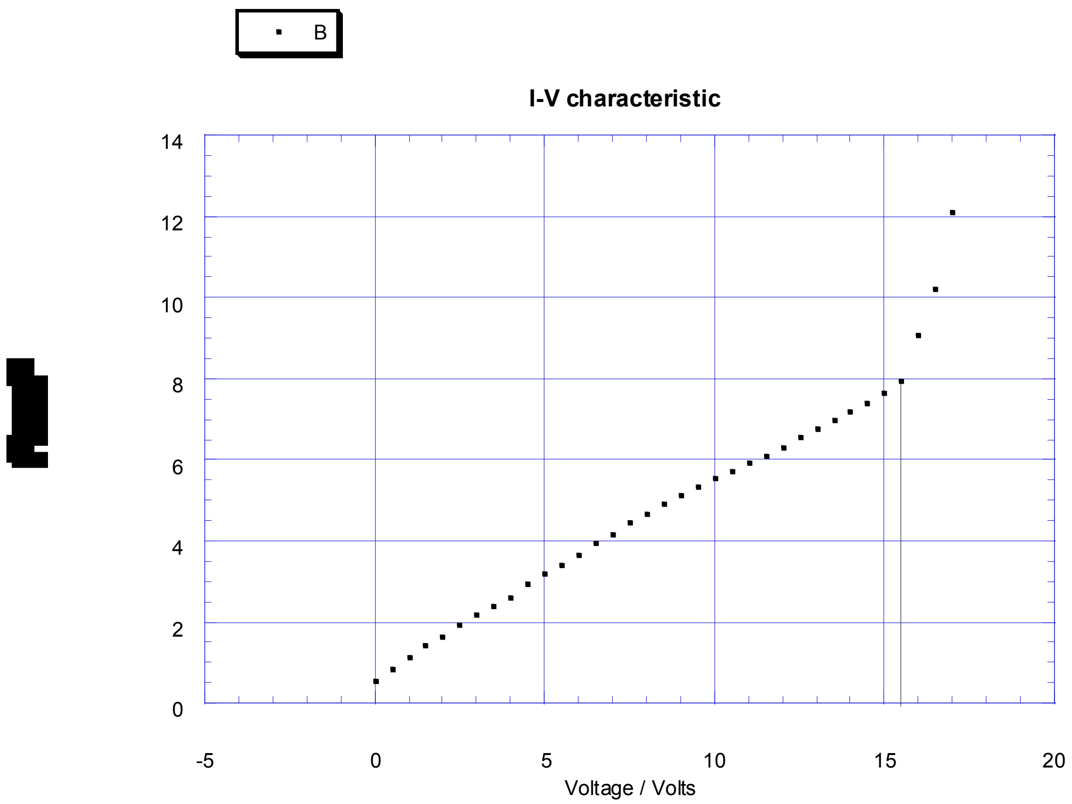
$$I_e = A n_e e \sqrt{\frac{k_B T_e}{2\pi m}}$$

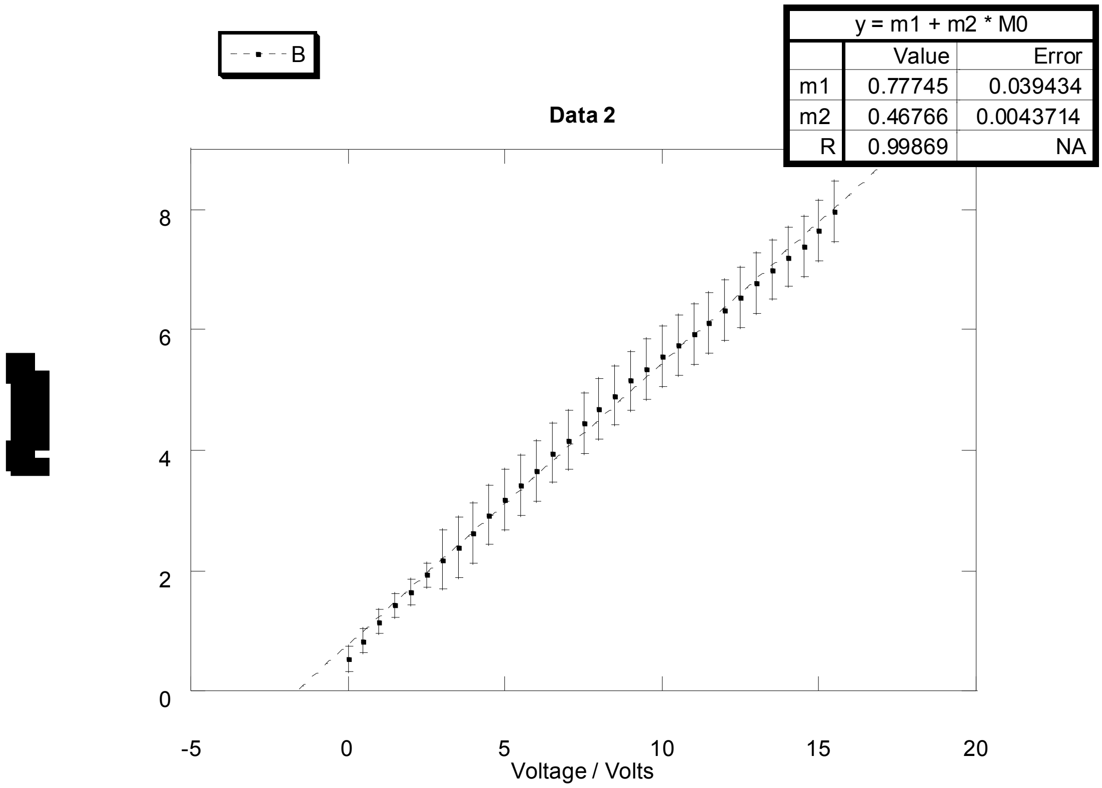
(11)

Method:

Part (i):

The apparatus was set up and the heater was turned to 6V in order to produce the requisite thermionic emission, as described above. The tube current *I* was measured for voltages in the range 0 to 18V in steps of 0.5V and the consequent *I-V* characteristic was obtained.





$$m_2 = 0.46766 \pm 0.00437 (mA)^{\frac{2}{3}} / V$$

$$m_2 = \left[2\pi\varepsilon_0 \left(\frac{4L}{9R}\right)\sqrt{\frac{2q}{m}}\right]^{\frac{2}{3}} \Rightarrow \frac{q}{m} = \frac{1}{2} m_2^{\frac{3}{2}} \left(\frac{1}{2\pi\varepsilon_0}\frac{9R}{4L}\right)^2$$

$$L = 0.224m$$

$$R = 0.015m$$

$$\varepsilon_0 = 8.85\times10^{-12} C/Vm$$

$$\frac{q}{m} = \frac{1}{2}\times\left[0.00046766 \pm 0.00000437 (A)^{\frac{2}{3}} / V\right]^3 \times \left(\frac{1}{2\times\pi\times(8.85\times10^{-12} C/Vm)} \times \frac{9\times0.224}{4\times0.015}\right)^2$$

$$\frac{q}{m} = 0.5\times1.0228\times10^{-10}\times1.4502\times10^{22} = 7\pm1\times10^{11} C/kg$$

This compares with the actual value of $\frac{q}{m} = 1.75\times10^{11} C/kg$.

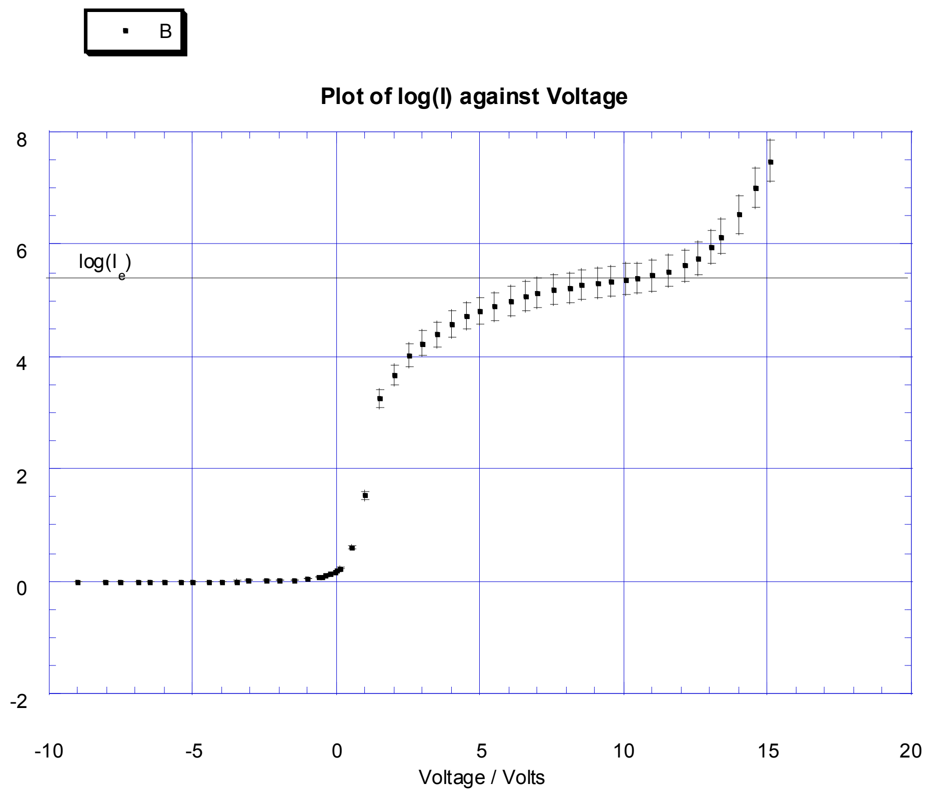
Part (ii)

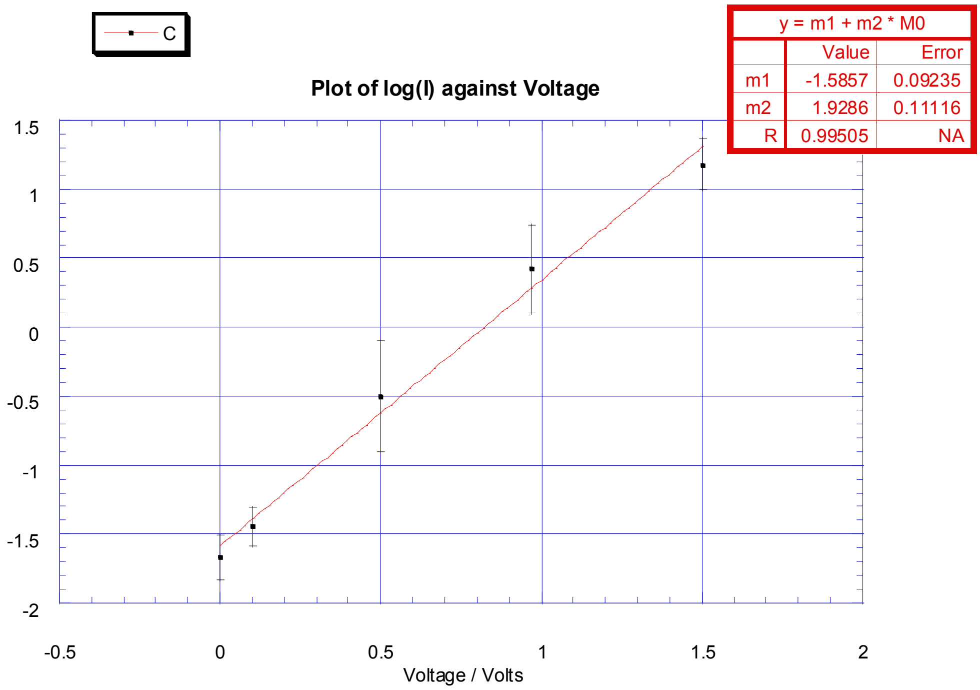
The apparatus was set up as required and a discharge voltage of 185V was applied to the argon (terminal 2) in order to create a plasma in the tube. This gave rise to a discharge current of 10mA.

The probe current as a function of voltage was measured for *V* in the range from -9V to 16V, and the resulting *I-V* characteristic was obtained.

log I against V was plotted, the linear part of the graph was identified and these linear datapoints were used, together with equation (11) to calculate the electron temperature.

The saturation current was also identified from this plot and this, together with equation (10) yielded the electron density.




C
Plot of log(I) against Voltage
y = m1 + m2 * M0
Value
Error
m1
-1.5857
0.09235
m2
1.9286
0.11116
R
0.99505
NA
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-0.5
0
0.5
1
1.5
2
Voltage / Volts