Langmuir Probes

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Plasma Physics Groep **LP14**

1 Electric Field and Electron Density

1.1 Electric field

The circuit can be drawn as follows:

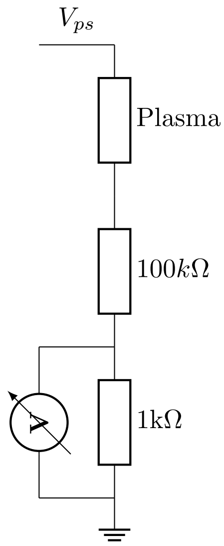


Figure 1: Pictographic representation of the circuit

Plasma Voltage

We first measured the voltage over the lowermost resistor (see figure 1) giving us the current in the plasma. We then also measured the probe voltage and the Power supply voltage. Using what we know about the circuit we could then infer the voltage over the plasma. E.g if we measured 3V on the lowermost resistor that means there's a 3mA current, if the power supply was set to 700V that means that (subtracting 3V and 300V) we have a Plasma voltage of 397 V.

Electric field

As we're dealing with a plasma that's homogeneous between the two probes, we can assume that the electric field is uniform. The electric field can thus be found by measuring the probe voltage and dividing it by the distance between the probe which was given to be 2cm

Electron current

Since the electron current is much larger than the current due to the ions, we can assume the following relation to find the electron density:

$$J = n_e \, e \, \mu_e \, E \tag{1}$$

with J the current density, n_e the electron density, μ the electron mobility. For argon it was given that $\mu = 0.33.10^6 \, \frac{cm^2 \, Torr}{V.s}$ and 4cm for the tube diameter. Since we can measure the current easily and calculate the electric field E, means that we can find the electron density n_e by rearranging equation 1. The results are given here below.

1.2 results

0.08 mBar

PowerSupply (V)	PlasmaCurrent (mA)	ProbeVoltage (V)	PlasmaVoltage (V)	ElectricField (V/m)	Electron density (cm^{-1})
779	3.0	8.24	476	412	6.58E+07
985	5.0	7.80	480	390	1.16E+08
1187	7.0	7.55	480	378	1.67E+08
1386	9.0	6.98	477	349	2.33E+08
1591	11.0	7.67	480	384	2.59E+08
1801	13.0	6.58	488	329	3.57E+08
2007	15.0	5.93	492	297	4.57E+08

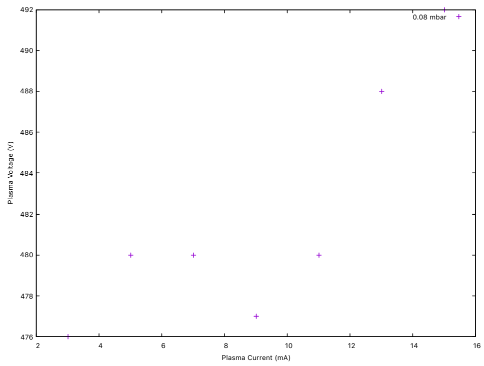


Figure 2: Plasma voltage i.f.o current for 0.08 mbar Argon plasma

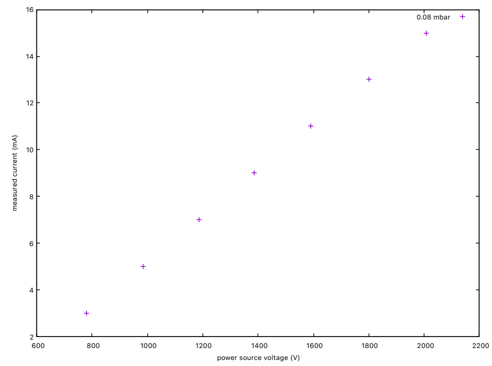


Figure 3: current i.f.o power supply voltage for 0.08 mbar Argon plasma

0.28 mBar

PowerSupply (V)	PlasmaCurrent (mA)	ProbeVoltage (V)	PlasmaVoltage (V)	ElectricField (V/m)	ElectronDensity (cm^{-1})
863	3.0	11.86	560	593	1.60E+08
1032	5.0	10.58	527	529	2.99E+08
1219	7.0	9.91	512	495.5	4.47E+08
1414	9.0	9.21	505	460.5	6.18E+08
1616	11.0	8.88	505	444	7.83E+08
1819	13.0	8.51	506	425.5	9.66E+08
2027	15.0	8.22	512	411	1.15E+09

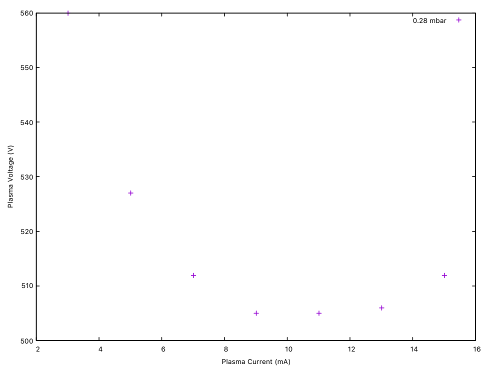


Figure 4: Plasma voltage i.f.o current for 0.28 mbar Argon plasma

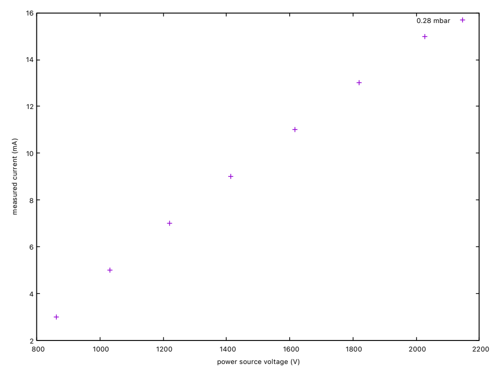


Figure 5: current i.f.o power supply voltage for 0.28 mbar Argon plasma

1.3 Theory

First off, we wish to point out that "stratisfaction" was observed for the 0.08mbar plasma:

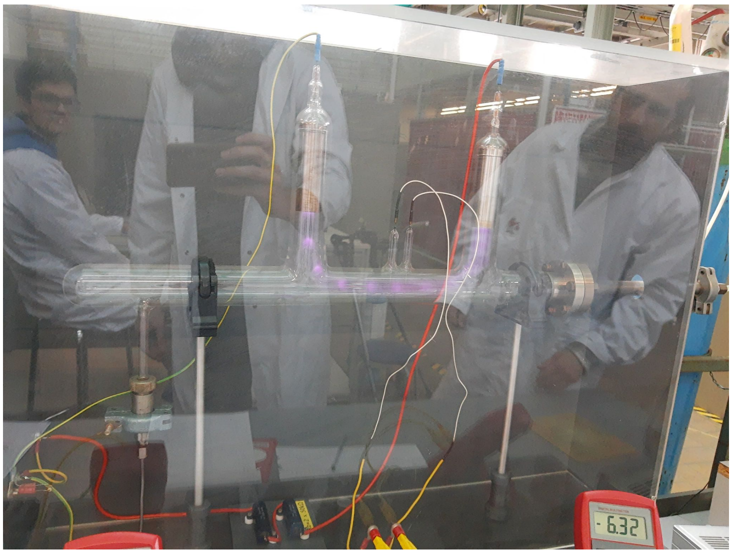
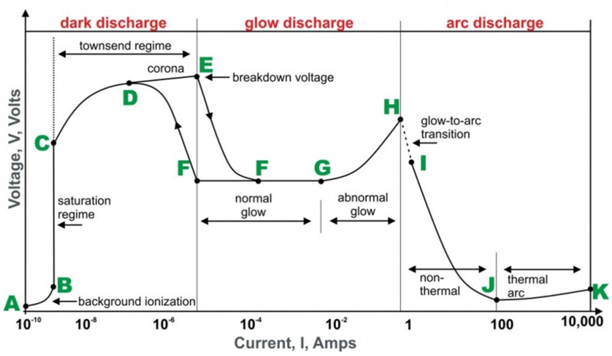


Figure 6: stratisfaction in the 0.08 mBar plasma

Which could have made the measurements less reliable.

Here is a graph showing the different discharge regimes:



1.3.1 0.28 mBar

Taking a look at figure 4) we can see that the 0.28 mBar plasma must be in the normal glow region a bit above the F point shown in the above figure. This implies that the gas broke down and moved into the normal glow discharge regime in which the voltage is almost independent of the current over several orders of magnitude in the discharge current.

1.3.2 0.08 mBar

Now looking at figure 2, the 0.08 mBar plasma could still be in the normal glow discharge state (as, due to the previously mentioned stratisfaction the tail going upwards was just a measuring error) or just about entering the abnormal glow state in which the voltage would increase significantly with the increasing total current in order to force the cathode current density above its natural value and provide the desired current.

2 Electron Temperature

2.1 Measurements

A general measurement is shown in figure 15, in the title on the figure 14.94mA is meant by 1494mA. Now this will be fitted and centered, this can be done quite easily by looking at the value for the probe voltage when the current was zero and shifting the fit afterwards as $(a+\text{shift})*x+b$. This shifting wasn't done for the middle part as that offset isn't needed. We did this for all the recorded data:[1]

406mA008mBar

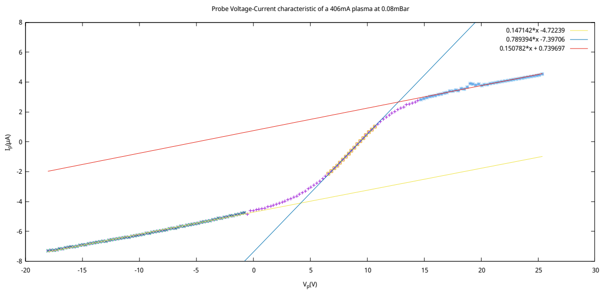


Figure 7: Measurement of the probe current vs voltage with fits at 0.08mBar and 406mA Plasma current

side	rico	offset
left	0.147142+/- 0.0008376 (0.569%)	-3.340638+/- 0.008933 (0.267%)
middle	0.789394+/- 0.003852 (0.488%)	-7.39706+/- 0.03358 (0.454%)
right	0.150782+/- 0.003752 (2.488%)	2.155630+/- 0.07614 (3.532%)

812mA008mBar

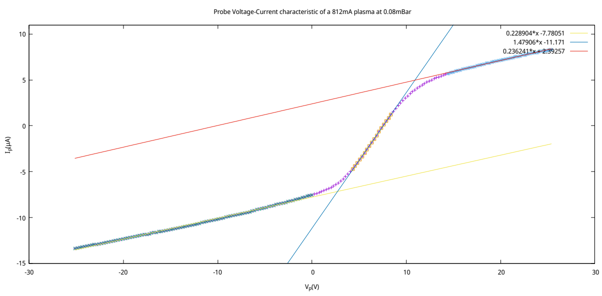


Figure 8: Measurement of the probe current vs voltage with fits at 0.08mBar and 812mA Plasma current

side	rico	offset
left	0.228904+/- 0.001364 (0.596%)	-5.624880+/- 0.01984 (0.353%)
middle	1.47906+/- 0.007794 (0.5269%)	-11.171+/- 0.05039 (0.4511%)
right	0.236241+/- 0.00182 (0.7705%)	4.191309+/- 0.03674 (0.8765%)

1490mA008mBar

side	rico	offset
left	0.367132+/- 0.002891 (0.7875%)	-10.808247+/- 0.04292 (0.3969%)
middle	2.39917+/- 0.02924 (1.219%)	-15.0895+/- 0.1878 (1.244%)
right	0.367526+/- 0.003432 (0.9339%)	7.903932+/- 0.06811 (0.8617%)

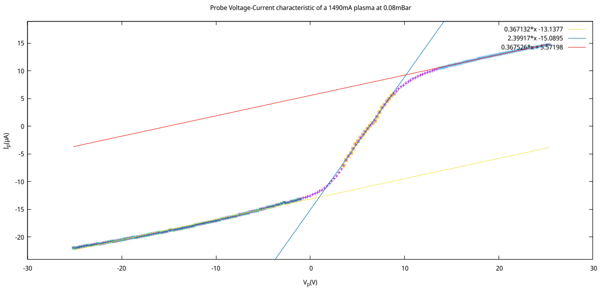


Figure 9: Measurement of the probe current vs voltage with fits at 0.08mBar and 1490mA Plasma current

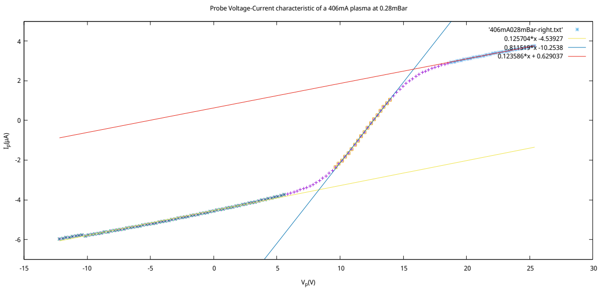


Figure 10: Measurement of the probe current vs voltage with fits at 0.28mBar and 406mA Plasma current

406mA028mBar

side	rico	offset
left	rico: 0.125704+/- 0.001075 (0.8553%)	-2.944086+/- 0.006622 (0.2249%)
middle	rico: 0.811519+/- 0.005646 (0.6957%)	-10.2538+/- 0.06705 (0.6539%)
right	rico: 0.123586+/- 0.001045 (0.8459%)	2.197343+/- 0.02318 (1.055%)

800mA028mBar

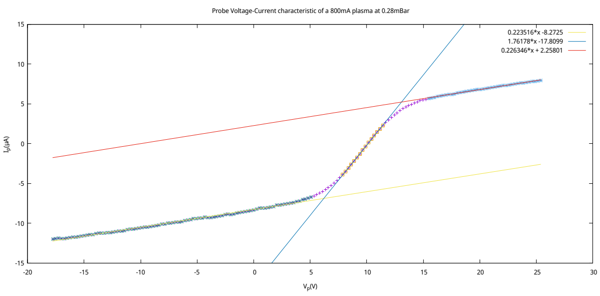


Figure 11: Measurement of the probe current vs voltage with fits at 0.28mBar and 800mA Plasma current

side	rico	offset
left	0.223516 +/- 0.001869 (0.836%)	-5.9746 +/- 0.0172 (0.9151%)
middle	1.76178 +/- 0.008654 (0.4912%)	-17.8099+/- 0.084 (0.4716%)
right	0.226346+/- 0.002143 (0.9467%)	4.555875 +/- 0.04423 (0.9708%)

1494mA028mBar

side	rico	offset
left	0.34387 +/- 0.002567 (0.7466%)	-12.643951+/- 0.03715 (0.2938%)
middle	3.54658 +/- 0.03119 (0.8795%)	-29.9715 +/- 0.2492 (0.8315%)
right	0.365177 +/- 0.003795 (1.039%)	8.959403+/- 0.07531 (0.841%)

[1] note that in the figures the measurement isn't centered, this is only done for the fitted parameters

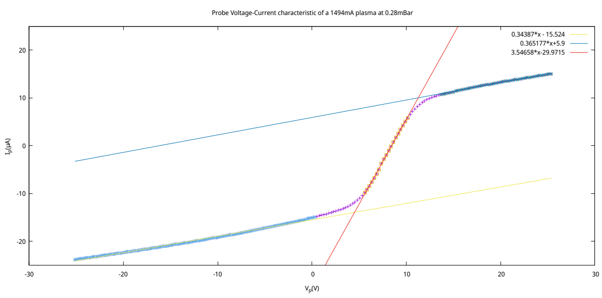


Figure 12: Measurement of the probe current vs voltage with fits at 0.28mBar and 1494mA Plasma current

2.2 Calculation

Looking at the formula for electron temperature:

$$T_e = \frac{e}{k} \cdot \left[2 \frac{I_{1+} \cdot I_{2+}}{I_{1+} + I_{2+}} \frac{1}{2 \frac{\mathrm{d}I}{\mathrm{d}V}\Big|_{I=0} - \frac{1}{2} \left(\frac{\mathrm{d}I_{1+}}{\mathrm{d}V} + \frac{\mathrm{d}I_{2+}}{\mathrm{d}V} \right)} \right] \tag{2}$$

we can re-write this in term of the fitted parameters:

$$T_e = \frac{e}{k} \cdot \left[2 \frac{\text{offset:right} \cdot \text{offset:left}}{\text{offset:right} + \text{offset:left}} \frac{1}{2 * \text{rico:middle} - \frac{1}{2} (\text{rico:right} + \text{rico:left})} \right] \tag{3}$$

Now to find the errors:

$$T_e \approx \frac{e}{k} \cdot \left[2 \frac{\mathrm{OR} \cdot \mathrm{OL}(1 \pm (\%^{OR} + \%^{OL})}{(\mathrm{OR} + \mathrm{OL})(1 \pm (\%^{OR} + \%^{OL})} \right] \cdot \left[\frac{1}{2 * \mathrm{RM} - \frac{1}{2} (\mathrm{RR} + \mathrm{RL})} \right] \tag{4}$$

$$\approx \frac{e}{k} \cdot \left[2 \frac{\mathrm{OR} \cdot \mathrm{OL}(1 \pm (\%^{OR} + \%^{OL})}{(\mathrm{OR} + \mathrm{OL})} \right] \cdot \left[\frac{1}{2 * \mathrm{RM} - \frac{1}{2} (\mathrm{RR} + \mathrm{RL})} \right] \tag{5}$$

$$\approx T_e^{\text{value}} [1 \pm (\%^{OR} + \%^{OL})] \tag{6}$$

Filling in this equation we get:
Now this percentual error assumes perfect measurements, it's however given that the error in voltage

current (mA)	pressure (mBar)	T_e
406	0.08	8.5 (Volt) $\frac{e}{k}$ ±3.799%
812	0.08	12.06 (Volt) $\frac{e}{k}$ ±1.2295%
1490	0.08	13.28 (Volt) $\frac{e}{k}$ ±1.2586%
406	0.28	11.61 (Volt) $\frac{e}{k}$ ±1.2799%
800	0.28	11.70 (Volt) $\frac{e}{k}$ ±1.8859%
1494	0.28	9.13 (Volt) $\frac{e}{k}$ ±1.1348%

and current measurements is 1% and the error in dI/dV measurements is 2%. We thus have to add 2% to each error to account for the multiplication of offsets in the numerator:
Now we look at the constants given by the particle data group [1] and fill in; as

current (mA)	pressure (mBar)	T_e
406	0.08	8.5 (Volt) $\frac{e}{k}$ ±5.799%
812	0.08	12.06 (Volt) $\frac{e}{k}$ ±3.2295%
1490	0.08	13.28 (Volt) $\frac{e}{k}$ ±3.2586%
406	0.28	11.61 (Volt) $\frac{e}{k}$ ±3.2799%
800	0.28	11.70 (Volt) $\frac{e}{k}$ ±3.8859%
1494	0.28	9.13 (Volt) $\frac{e}{k}$ ±3.1348%

$$k = 8.617333262...10^{-5} eVK^{-1} \tag{7}$$

And voltage [V] * elementary charge [C] = eV [J = C*V], we get:
We show a plot of these values in figures 13 and 14

current (mA)	pressure (mBar)	T_e (Kelvin)
406	0.08	98638 ±5720
812	0.08	139950 ±4561
1490	0.08	154108 ±5022
406	0.28	134729 ±4419
800	0.28	135773 ±5276
1494	0.28	105949 ±3321

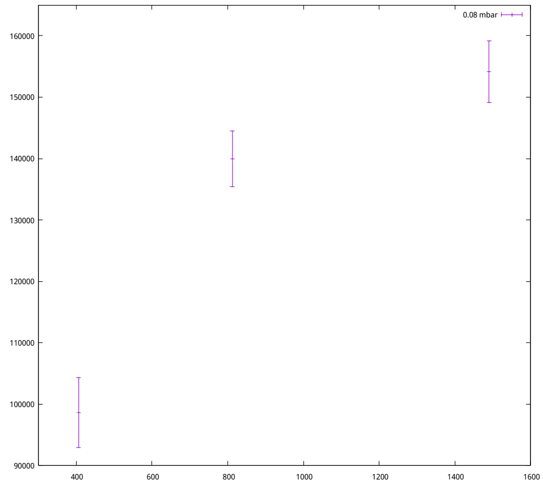


Figure 13: Electron temperature in function of the discharge current for the 0.008 mbar gas

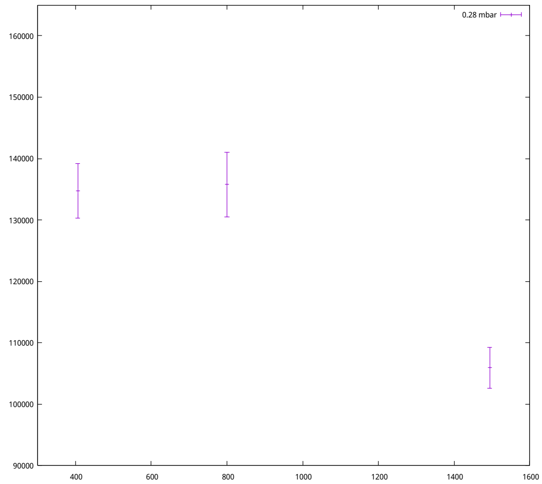


Figure 14: Electron temperature in function of the discharge current for the 0.028 mbar gas

2.3 Dependence of T_e and n_e on plasma operational parameters

First off, when looking at the results in section 1.2, it is clear that the electron density increases with the pressure. Which is logical as the rise in pressure is caused by the rise in the amount of plasma particles. Secondly, it also increases with the applied power supply voltage.

Looking at the T_e we can deduce that it is higher for lower pressure. Which follows from the fact that lower pressures make it so that the electron particles have a longer mean free path which gives the electrons more time to accelerate. If we take a look at the theory we would also expect it to increases with the current, but looking at our measurements depicted in figure 14 we see that for the last measurement at 1494mA, the electron temperature is suddenly lower. This can be due to a measurement error.

3 Difference between a Langmuir and a double probe

A Langmuir or single probe consists of one electrode biased relative to the vessel. This is contrary to the double probe where an electrode is biased relative to a second electrode, rather than to the ground. As the double probe and the plasma are at floating potential, no net current flows into or from the plasma. Thus the electron density n_e will not affect the I_p/V_p characteristics of the double probe and thus can't be measured with it.

References

[1] R. L. Workman and Others, "Review of Particle Physics," *PTEP*, vol. 2022, p. 083C01, 2022.

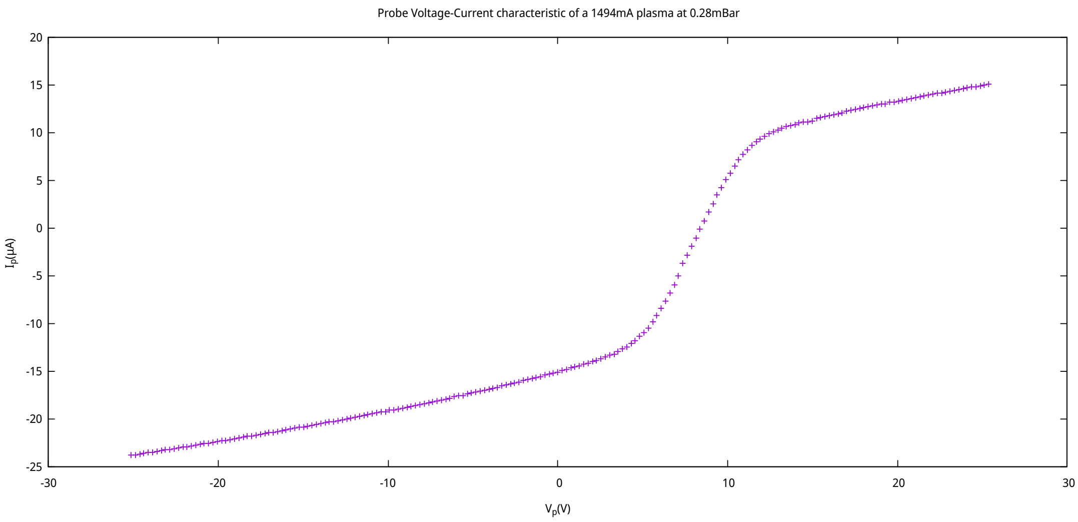


Figure 15: Measurement of the probe current vs voltage at 0.08mBar and 14.94mA Plasma current