LANGMUIR PROBE SYSTEM

Measure the fundamental plasma parameters with the industry standard Langmuir Probe

https://www.impedans.com/langmuir-probe

Impedans
PLASMA MEASUREMENT

The Langmuir Probe System

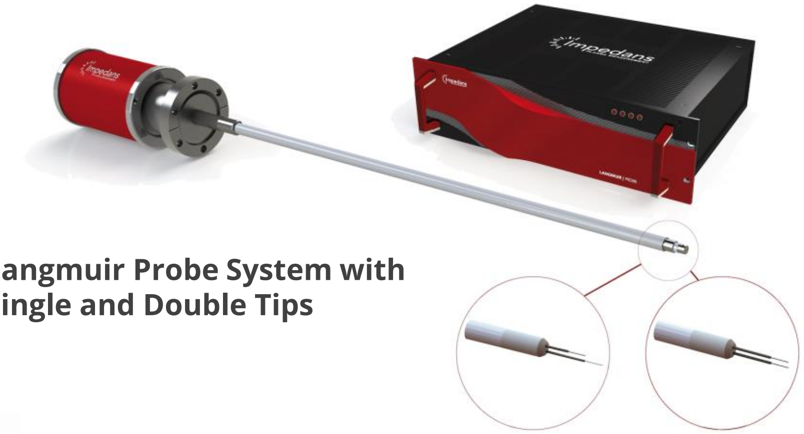
Measure the fundamental plasma parameters with the industry standard Langmuir Probe

Parameters Measured:

- ✓ Plasma potential
- ✓ Floating Potential
- ✓ Charged Particle Densities (ions and electrons)
- ✓ Electron Temperature
- ✓ Electron Energy Probability Function (EEPF)
- ✓ All of the above can automatically be measured spatially with the linear drive addition

Advantages of the Impedans Langmuir Probe:

- ✓ 80 MHz sampling rate, allowing for plasma characterization with μs resolution during pulsing
- ✓ Single and double probe exchangeable head
- ✓ RF compensated for up to 5 frequencies
- ✓ State of the art plasma models built into the software for automatic data analysis
- ✓ Over 100 publications using this hardware, trusted by universities and industry alike: impedans.com/langmuir-applications

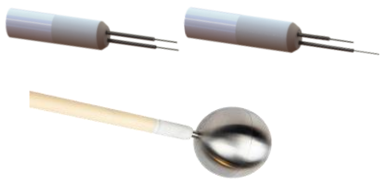


Langmuir Probe System with Single and Double Tips

Langmuir Probe System with Linear Drive

Key Features

Interchangable probe heads



Compatible with majority of plasma excitation methods

DC, pulsed DC, RF, pulsed RF, microwave and other plasma excitation methods.

Integrated RF compensation filters

RF compensated up to 5 frequencies in one probe.

Automated tip cleaning function

Plasma electron bombardment is used to remove oxides and insulating layers.

Integrated linear drive mechanism

Linear drive mechanism provides automatic spatial plasma uniformity.

Advanced software

State of the art plasma models built into software for automatic data analysis. Intuitive and user friendly

External pulse synchronization

Time averaged, time trend, synchronized pulse profile and triggered fast-sweep modes.

Variety of Probe Options

Solid shaft (standard and high temperature), flexible and substrate-level sensors available to serve many plasma chamber geometries

Technical Specifications

Parameters Measured	Range
Sampling Rate	80 MHz
Floating Potential	-145 V to +145 V
Plasma Potential	-100 V to +145 V
Plasma Density	$10^6 \ to \ 10^{13} \ cm^{-3}$
Ion Current Density	1 $\mu A/cm^2$ to 300 mA/cm^2
Electron Temperature	0.1 eV to 15 eV
EEPF (Electron Energy Probability Function)	0 eV to 100 eV

- ✓ For more detailed specifications and different models available, visit https://www.impedans.com/langmuir-probe
- ✓ To see if the probe is suitable for your plasma application, see the applications list at impedans.com/langmuir-applications
- ✓ To arrange a technical discussion, contact support@impedans.com

02-0308-01

Single Probe with DC Reference
(Plasmas with a ground; < 10 Torr)

02-0352-01

Double Probe
(un-grounded plasmas; all pressures)

Spherical Probe
(low density plasmas)

02-0306-01

Technical Specifications

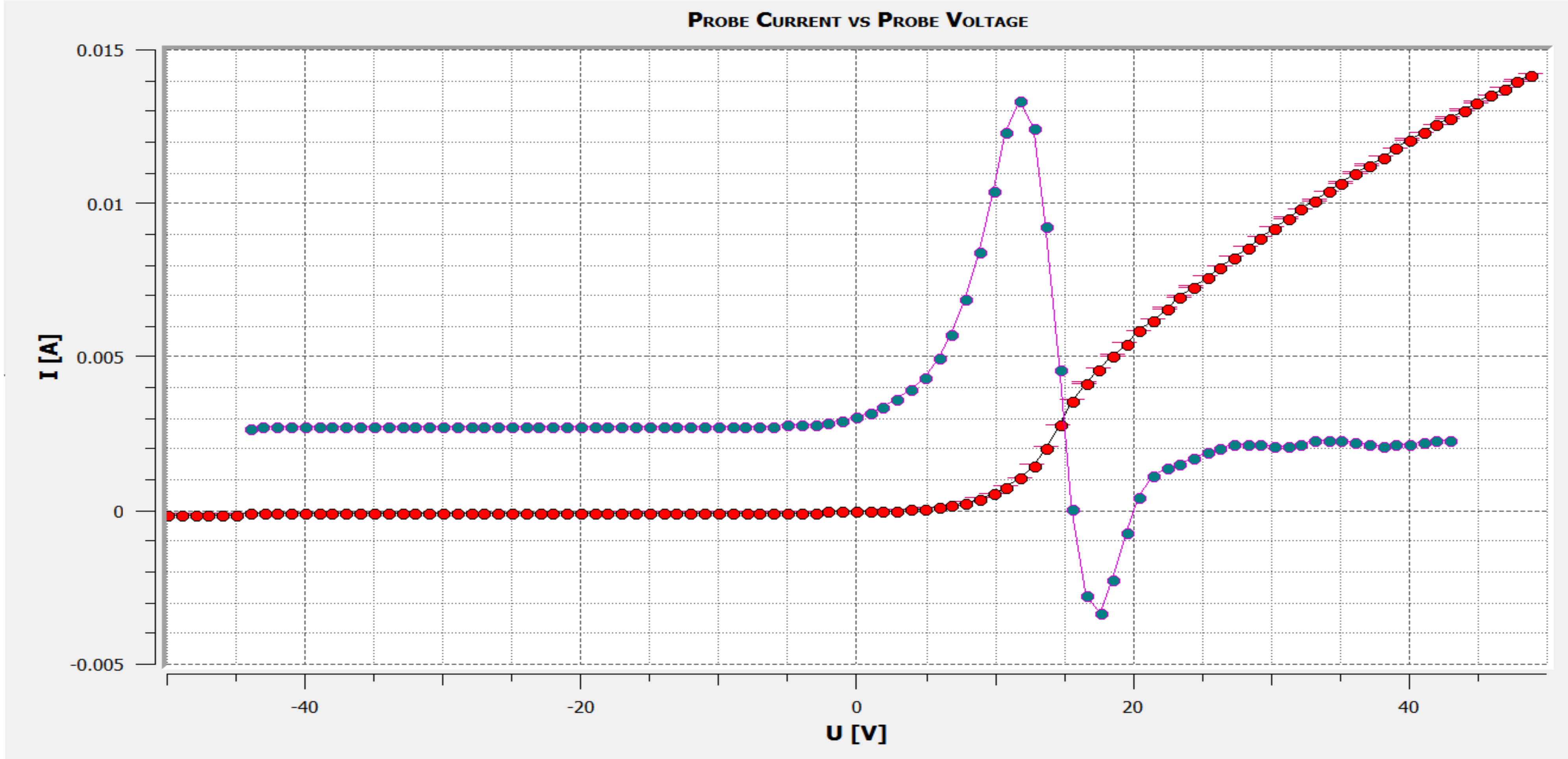
Probe Specifications	Range
Probe shaft diameters available	10 mm (standard), 6.5 mm (high temp, single)
Probe tip materials available	Tungsten (Noble); Tantalum and Platinum (Reactive, ex. Oxygen)
Probe types	Single with DC Reference, Double, Mach, Spherical, Planar (10 mm shaft), Single (6.5 mm shaft)
Vacuum Flanges	CF40 default; Adaptors on request; Adjustable flanges available
Temperature Limits	230C ($Air\ cooled$), 125C ($No\ cooling$), 900C (6.5 mm)
RF Compensation	Up to 5 filters (10 mm)
TTL input trigger; Time Resolution	1 Hz to 1 MHz; 12.5 ns (no filters), 1 us (filters)
Accessories	Right angle adaptors; 4 mm shaft
Pressure Range	Max 10 Torr (Single, Planar, Spherical), Max atmospheric (Double, Mach)

Right Angle Adaptor

4 mm shaft adaptor

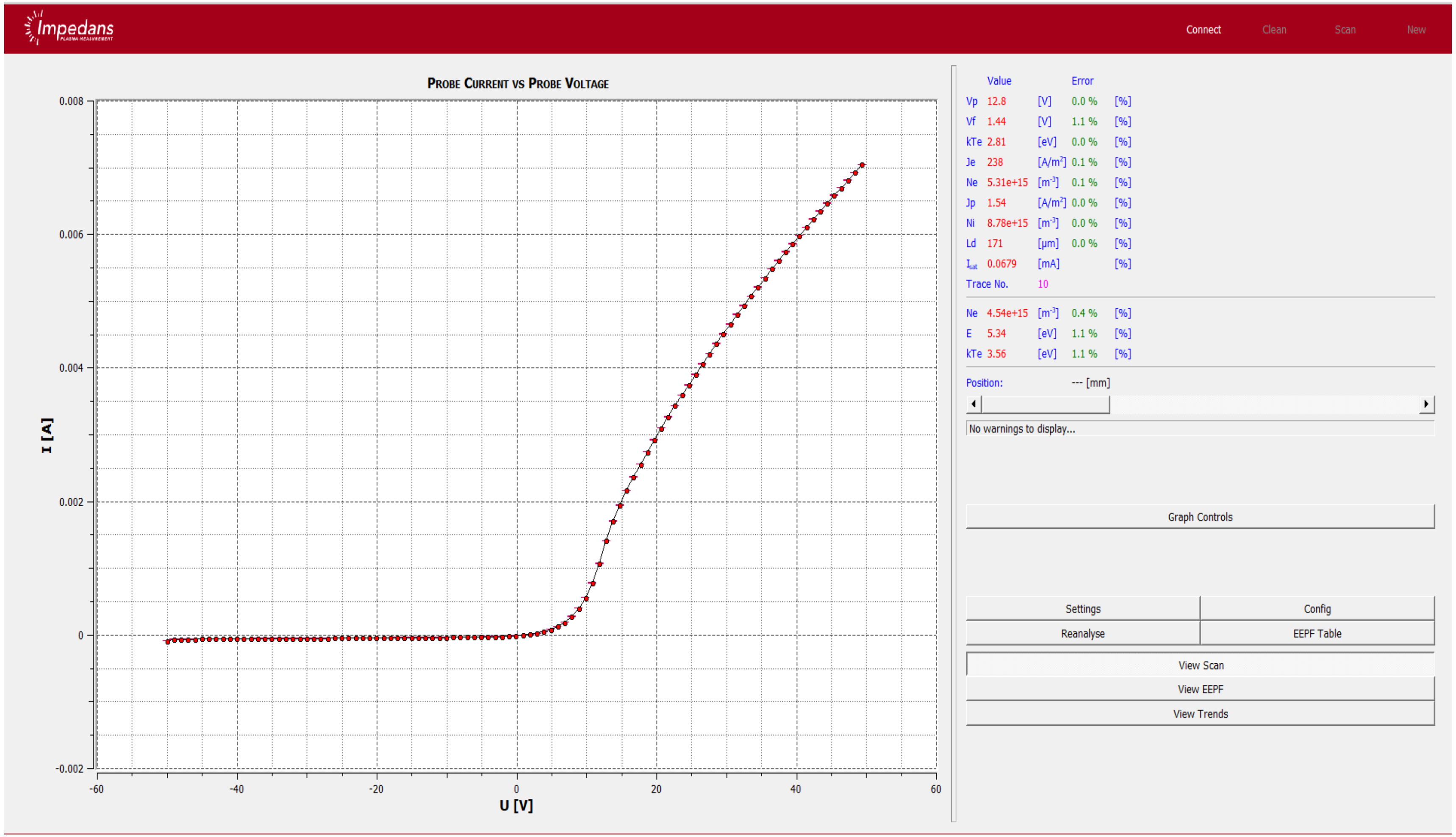
Langmuir Probe with an Adjustable Flange

Example Data: VI curve and second derivative for a Single Probe



Example Data: Single Probe Parameters

- ✓Plasma Potential (Vp)
- ✓Floating Potential (Vf)
- ✓Electron Temperature (kTe)
- ✓Electron Current Density/Flux (Je)
- ✓Electron Density (Ne)
- ✓Ion Current Density/Flux (Jp)
- ✓Ion Density (Ni)
- ✓Debye Length (Ld)
- ✓Ion Saturation Current (Isat)



	Value		Error	
Vp	12.8	[V]	0.0 %	[%]
Vf	1.44	[V]	1.1 %	[%]
kTe	2.81	[eV]	0.0 %	[%]
Je	238	[A/m²]	0.1 %	[%]
Ne	5.31e+15	[m⁻³]	0.1 %	[%]
Jp	1.54	[A/m²]	0.0 %	[%]
Ni	8.78e+15	[m⁻³]	0.0 %	[%]
Ld	171	[µm]	0.0 %	[%]
I_{sat}	0.0679	[mA]		[%]
Trace No.		10		
Ne	4.54e+15	[m⁻³]	0.4 %	[%]
E	5.34	[eV]	1.1 %	[%]
kTe	3.56	[eV]	1.1 %	[%]

Position: --- [mm]

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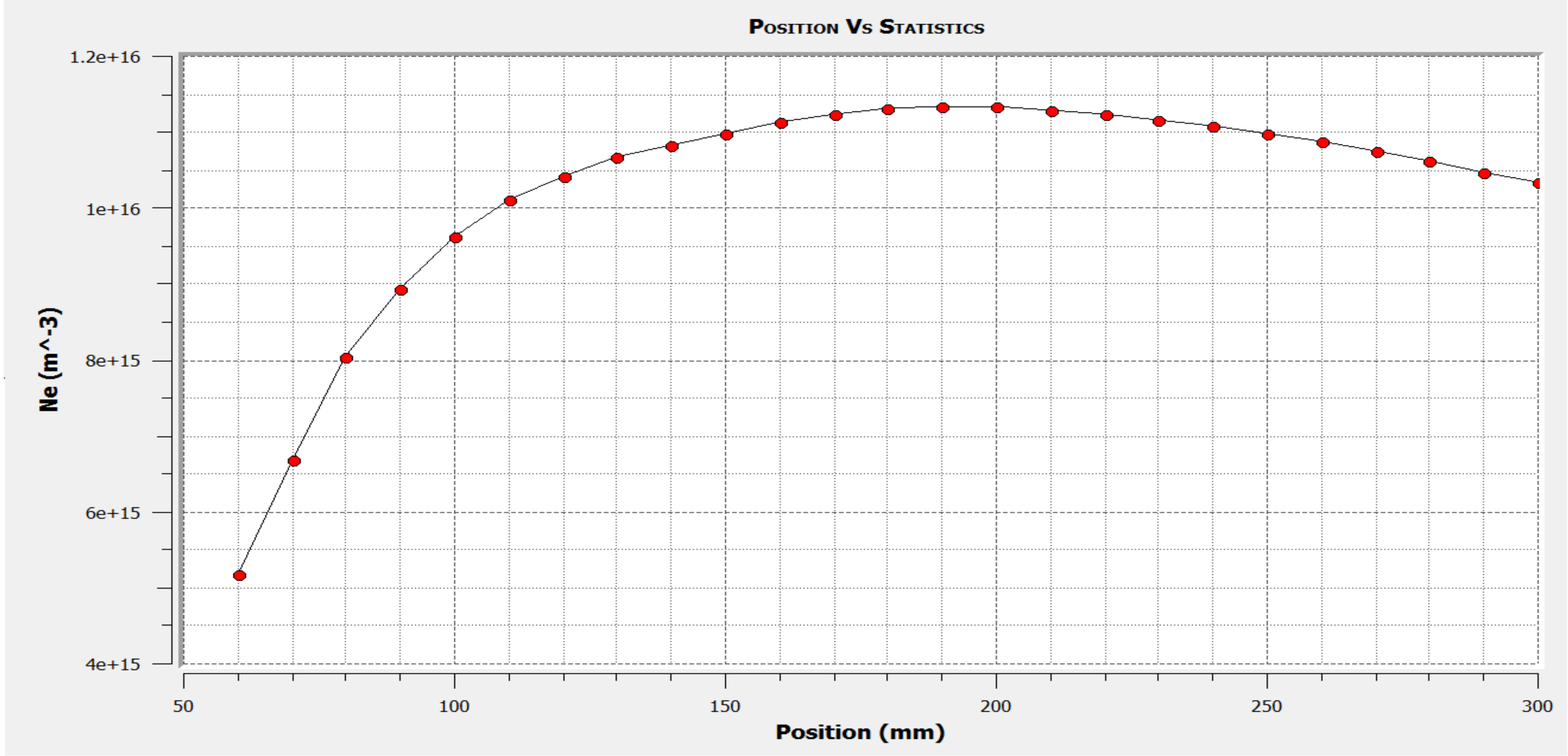
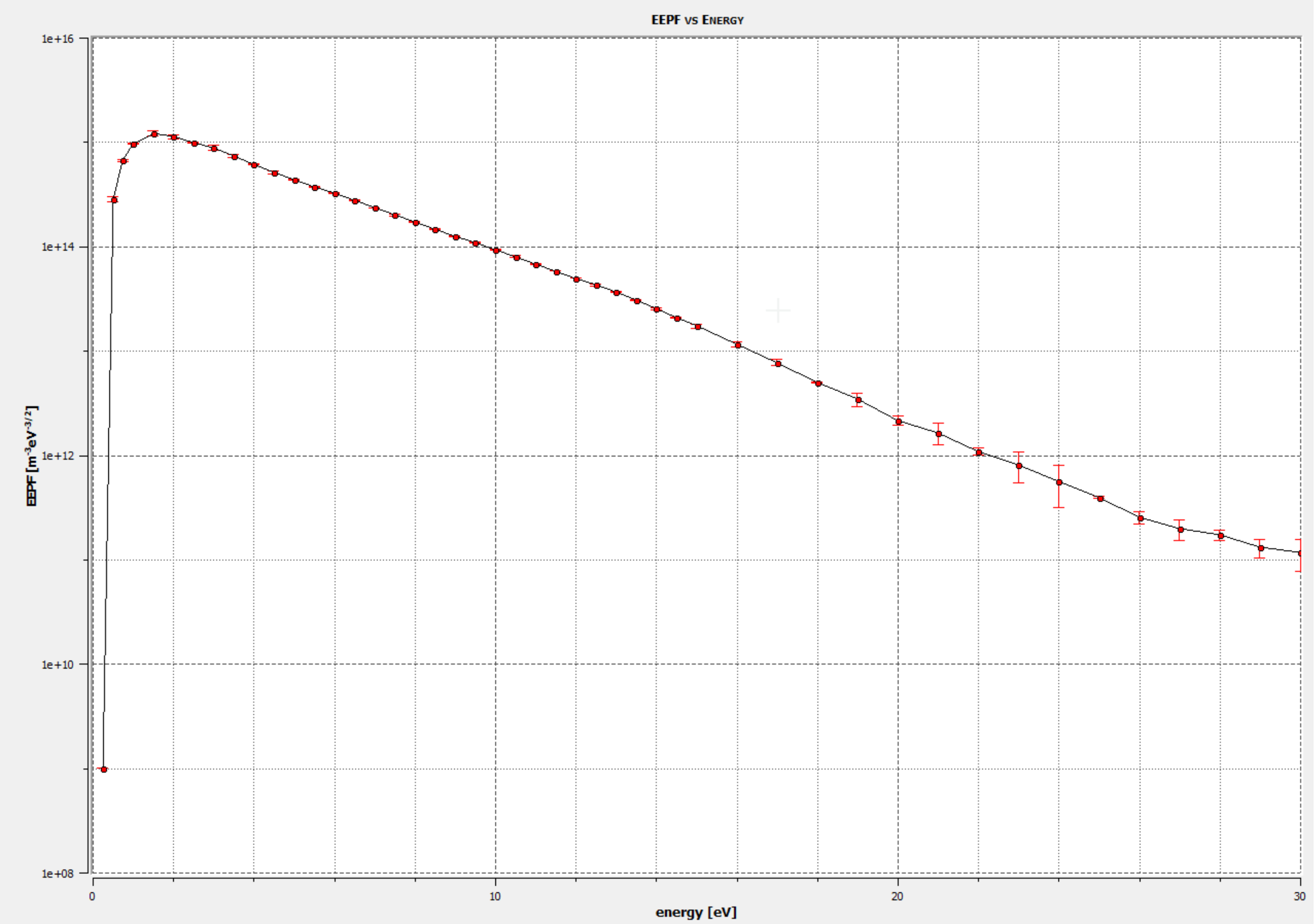
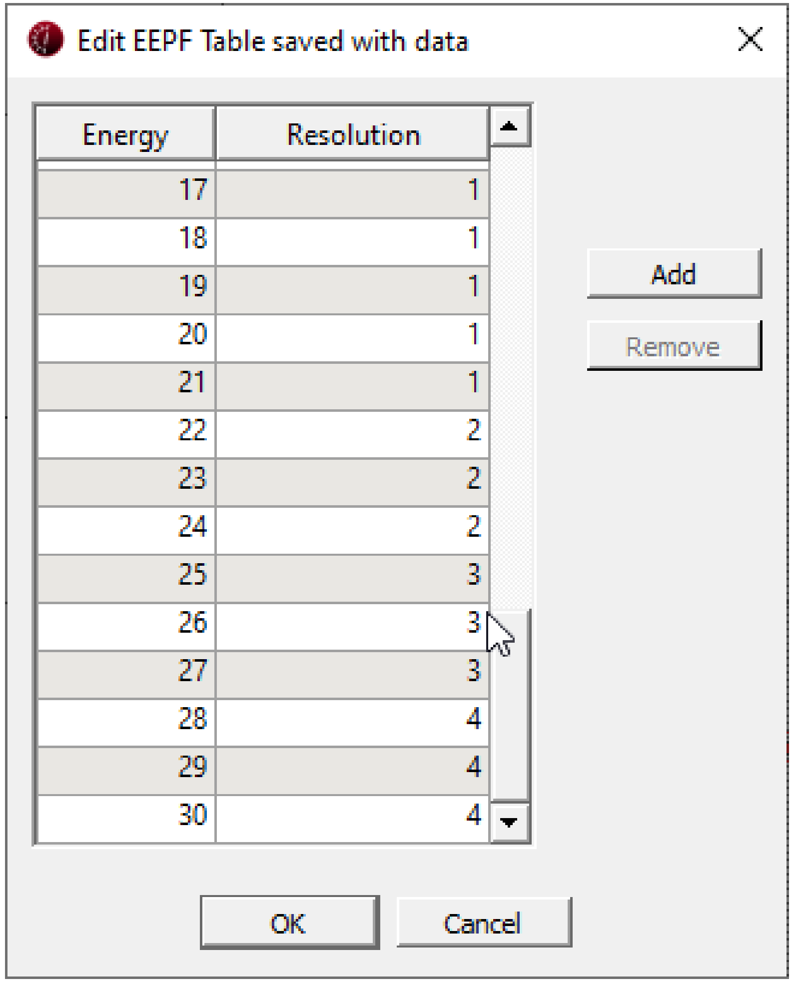
Example Data: Electron Density as a function of position over a 300mm wafer



Example Data: Electron Energy Probability Function (EEPF)

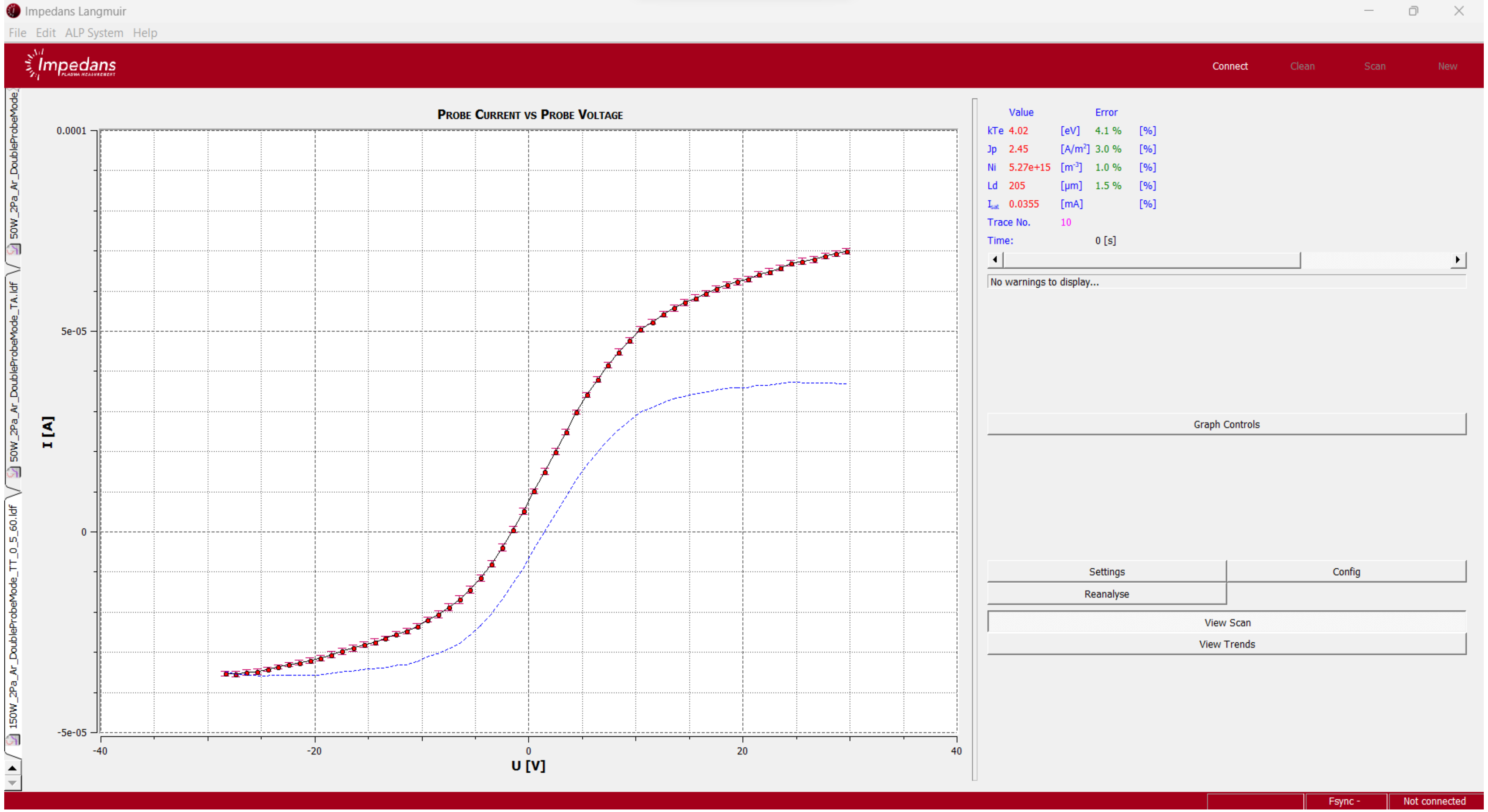




Energy	Resolution
17	1
18	1
19	1
20	1
21	1
22	2
23	2
24	2
25	3
26	3
27	3
28	4
29	4
30	4

Example Data: Double Probe Parameters

- ×Plasma Potential (Vp)
- ×Electron Current Density/Flux (Je)
- ×Electron Density (Ne)
- ×Floating Potential (Vf)
- ✓Electron Temperature (kTe)
- ✓Ion Current Density/Flux (Jp)
- ✓Ion Density (Ni)
- ✓Debye Length (Ld)
- ✓Ion Saturation Current (Isat)



	Value		Error	
kTe	4.02	[eV]	4.1 %	[%]
Jp	2.45	[A/m²]	3.0 %	[%]
Ni	5.27e+15	[m⁻³]	1.0 %	[%]
Ld	205	[µm]	1.5 %	[%]
I_{sat}	0.0355	[mA]		[%]

Trace No. 10

Time: 0 [s]

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Langmuir Applications

Measurement of Microsecond Resolution Electron Density Evolution in a Pulsed ICP

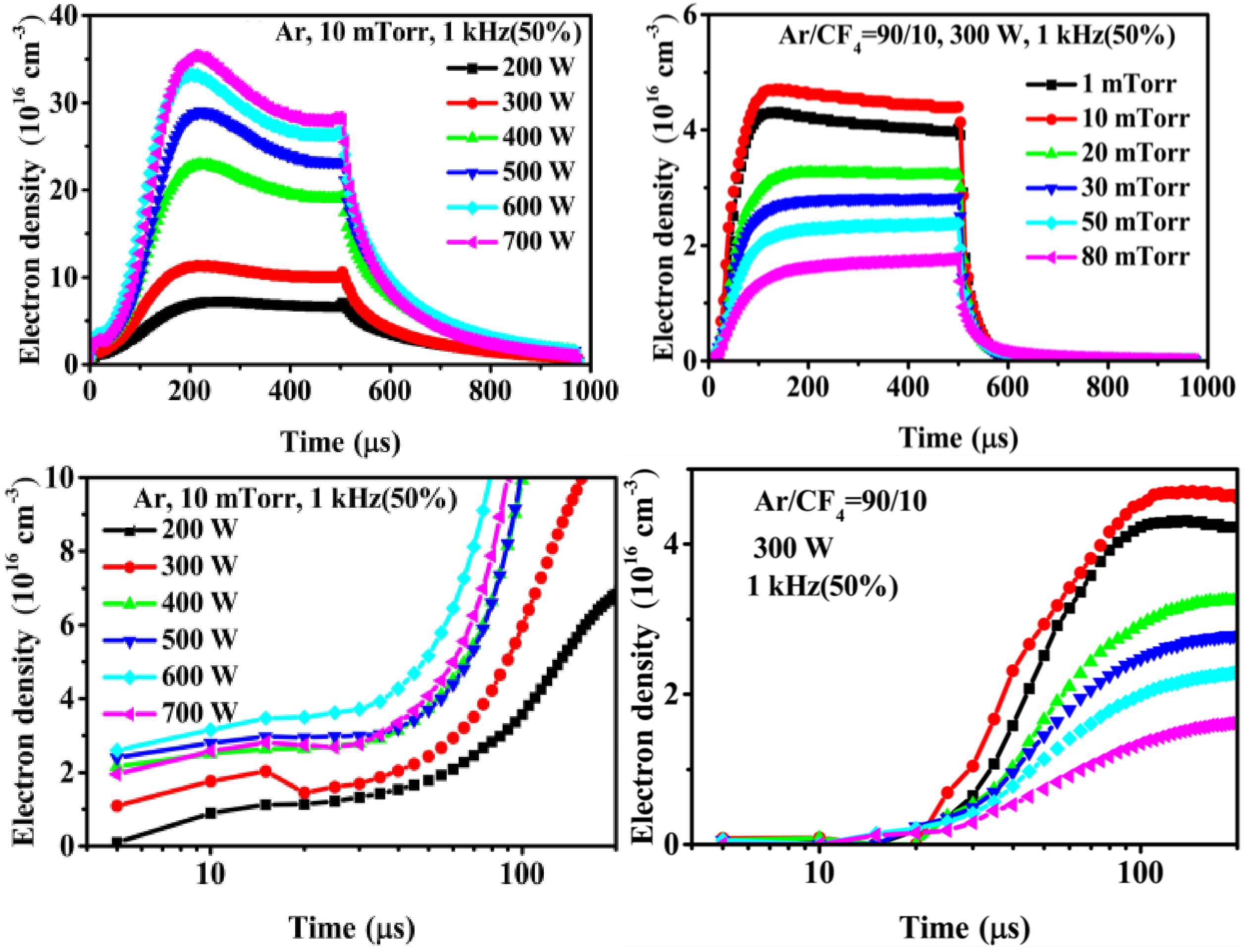
Complex Transients of Input Power and Electron Density in Pulsed Inductively Coupled Discharge

DOI: 10.1063/1.5114661

The objective of this paper was to measure, on a microsecond timescale, the evolution of the plasma density in an inductively coupled plasma as a function of power and pressure for both Ar and (90:10) gas mixtures.

Some example data is shown to the right

https://www.impedans.com/langmuir-and-octiv-application-note-lp15-oc08



Examples are shown of the Temporal evolution of the electron density as a function of the input power in a 10 mTorr Ar pulsed plasma and as a function of the Pressure in an plasma.

Spatial Measurement of Plasma Parameters in a Two-Chamber ICP

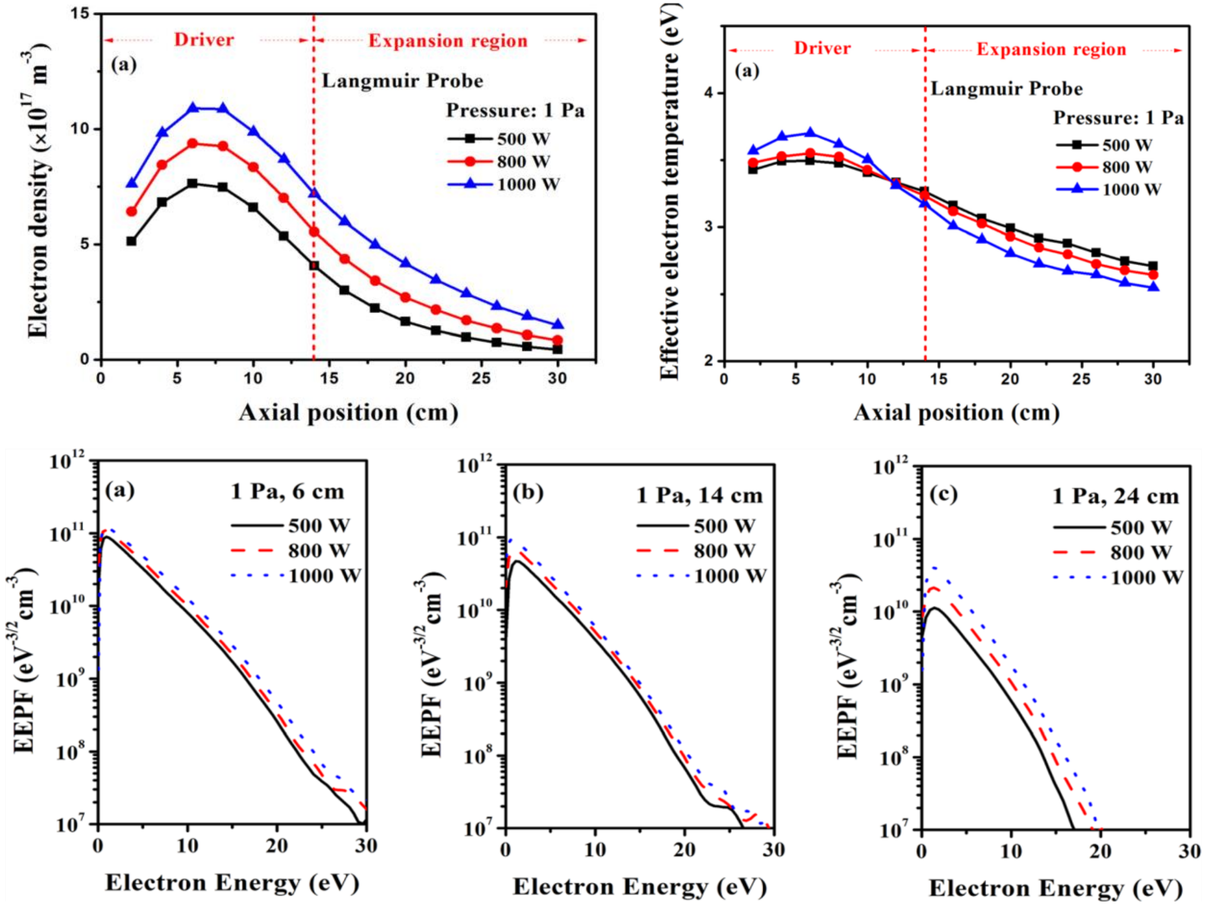
Non-local electron kinetics and spatial transport in radio-frequency two-chamber inductively coupled plasmas with argon discharges

DOI: 10.1063/1.4986495

The objective is to measure the spatial characteristics of the plasma parameters along the axis of the chamber (results shown) and along the radial direction of the chamber (not shown here).

Some example data is shown to the right

https://www.impedans.com/langmuir-and-octiv-application-note-lp18-oc09



Examples of the spatial behaviour of the electron density and temperature along the axis of the chamber for a variety of powers. Also shown are some sample EEPF's at various positions for the same powers

Langmuir Theory

Sheath Expansion Models

I_i – The ion current for collisionless sheaths

Comprehensive studies [1 - 4] have shown (for collisionless probe sheaths) that the ion current to a cylindrical probe, incorporating sheath expansion, can be expressed with excellent accuracy as

$$I_i = I_0 a(-X)^b \qquad (1)$$

where I_0 is the ion flux at the sheath edge and X is the dimensionless probe potential given by $X = \left(V - V_p\right)/kT_e$, where V and V_p are the probe and plasma potential respectively and kT_e is the electron temperature in eV. The coefficients *a* and *b* are parameters relating to the probe radius r_p, the Debye length λ_D and the probe geometry. Analytical expressions for the parameters a and b have been given for a cylindrical probe, in terms of r_p/λ_D, by Narasimhan and Steinbruchel [4]. For a cylindrical probe:

$$\begin{aligned} a_{cyl} &= 1.18 - 0.0008\left(\frac{r_p}{\lambda_D}\right)^{1.35} \\ b_{cyl} &= 0.0684 + \left(0.722 + 0.928\, r_p/\lambda_D\right)^{-0.729} \end{aligned} \qquad (2)$$

For certain probe geometries, under certain plasma conditions, the hemispherical sheath that develops around the end face of the probe tip can provide a significant contribution to the probe ion current.

Parameters *a* and *b* for the hemispherical end sheath are also given:

$$\begin{aligned} a_{sph} &= 1.98 + 4.49\left(\frac{r_p}{\lambda_D}\right)^{1.31} \\ b_{sph} &= -2.95 + 3.61\left(\frac{r_p}{\lambda_D}\right)^{-0.0394} \end{aligned} \qquad (3)$$

The total ion current collected by real cylindrical probe is assumed to be the sum of the ion current to an ideal cylindrical probe *I_i(cyl)* and the ion current to a hemisphere at the end of the probe *I_i(sph)* and are related by

$$\frac{I_i(sph)}{I_i(cyl)} = \left(\frac{r_p}{L_p}\right)\left(\frac{a_{sph}}{a_{cyl}}\right)(-X)^{\Delta b} \qquad (4)$$

where *Δb* = b_{sph} - b_{cyl} and L_p is the probe tip length. Equation 1 is initially solved for I_0 using the probe current at a large negative voltage. Then Ii to the probe for all probe voltages is calculated using I_0. The electron current I_e is obtained by subtracting I_i from the probe current. Figure 1 shows an IV characteristic including the calculated ion current and electron current.

Sheath Expansion Models

I_i – The ion current for collisionless sheaths

At higher pressures when the ions begin to undergo collisions with the neutral atoms in the probe sheath this theory fails and so a second theory is implemented.

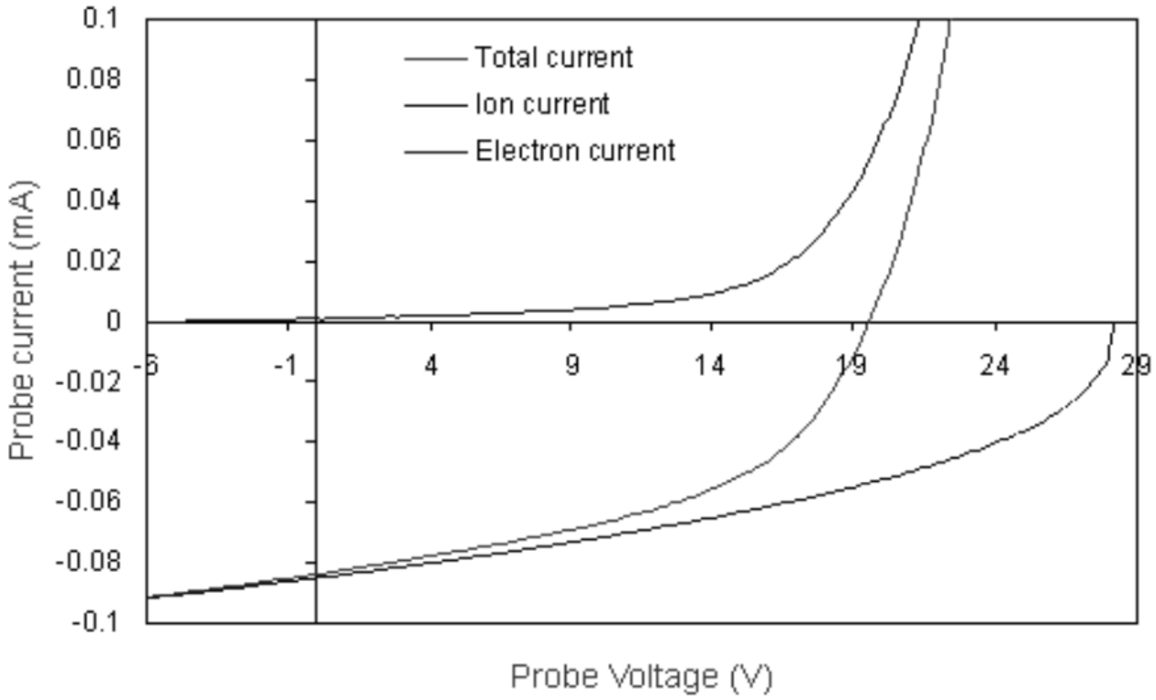


Figure 5-3: IV characteristic in the ion current region, showing total, ion and electron probe currents

I_i – The ion current for collisional sheaths

Recent studies [5-7] have led to the development of models for probe ion current in the presence of ion collisions in the sheath and have been demonstrated to work up to high pressure. One of the most accurate has been shown to be [8] that of Zakrzewski and Kopiczynski [7]. This model is expressed in terms of the collisionless model described by equations 1 and 4 as:

$$I_i = [I_0 a(-X)^b + I_i(sph)]\gamma_1\gamma_2 \tag{5}$$

where $\gamma1$ and $\gamma2$ are factors which depend on the number of collisions in the sheath and is based on a theory proposed by Allen, Boyd and Reynolds [9] (ABR) such that:

$$\boldsymbol{\gamma_1 = \chi_i\left(\frac{I_i(ABR)}{I_i(LAF)} - 1\right)} \qquad \boldsymbol{\gamma_2 = \frac{3 - 2e^{-\chi_i}}{1 + 2\chi_i}} \qquad \textbf{If } \boldsymbol{\chi_i < 1}$$

$$\boldsymbol{\gamma_1 = \frac{I_i(ABR)}{I_i(LAF)}} \qquad \boldsymbol{\gamma_2 = \frac{3 - e^{-\chi_i}}{2(1 + 2\chi_i)}} \qquad \textbf{If } \boldsymbol{\chi_i > 1} \tag{6}$$

Sheath Expansion Models

I_i – The ion current for collisional sheaths

where $I_i(ABR)$is the current to the probe in the collisional regime, $I_i(LAF)$ is the current to the probe in the collisionless regime given by equation 1, and χ_i is the number of collisions in the sheath, defined by

$$\chi_i = \frac{r_s - r_p}{\lambda_i} \qquad (7)$$

Where r_s and r_p are the sheath and probe radii respectively and λi is the ion mean free path. An analytical fit for r_s-r_p is used [7]:

$$r_s - r_p = \lambda_D \sqrt{0.59 + 1.86 r_p/\lambda_D(-X + 3.5) - 4} \qquad (8)$$

We use the analytical expression for $Ii(ABR)$proposed by Klagge and Tichy [5] i.e. $Ii(ABR) = a\,(-X/\mathrm{b})^{c}$, with coefficients:

$$\begin{aligned} a &= \left(r_p + 0.6\right)^{0.05} + 0.04 \\ b &= 0.09(e^{\lambda_D/r_p} + 0.08) \\ c &= \left(r_p/\lambda_D + 3.1\right)^{-0.6} \end{aligned} \qquad (9)$$

The implementation of this model allows the Langmuir Probe system to give accurate measurements up to discharge pressure of 10 Torr.

References

[1] J.G. Laframboise, Report No. 100, University of Toronto UTIAS, 1966
[2] Ch. Steinbruchel, Vac. Sci. Technol. A, 8, 1663, 1990
[3] A. Karamcheti and Ch. Steinbruchel, Vac. Sci. Technol. A, 17, 3051, 1999
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[6] L. Talbot and Y.S. Chou, 6th Rarefied Gas Dynamics Conference ed. Academic Press, New York, 1723, 1966
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[8] A. Rousseau, E. Teboul and S. Bechu, J. App. Phys, 98, 083306, 2005
[9] J.E. Allen, R.L.F. Boyd, and P. Reynolds, Proc. Phys. Soc. London, Sect. B, 70, 112, 1957

Single Probe: Plasma Parameter Equations

Plasma Potential (Intersecting Slope method):

$$V_p = \frac{-b + \ln\left(I(V_{max})\right) - \frac{V_{max}}{kT_e}}{a - \frac{1}{kT_e}} \qquad (10)$$

Electron Temperature:

$$\frac{1}{kT_e} = \frac{I(V_p)}{\int_{V_f}^{V_p} I_e(V)\, dV} \qquad (11)$$

Electron Density:

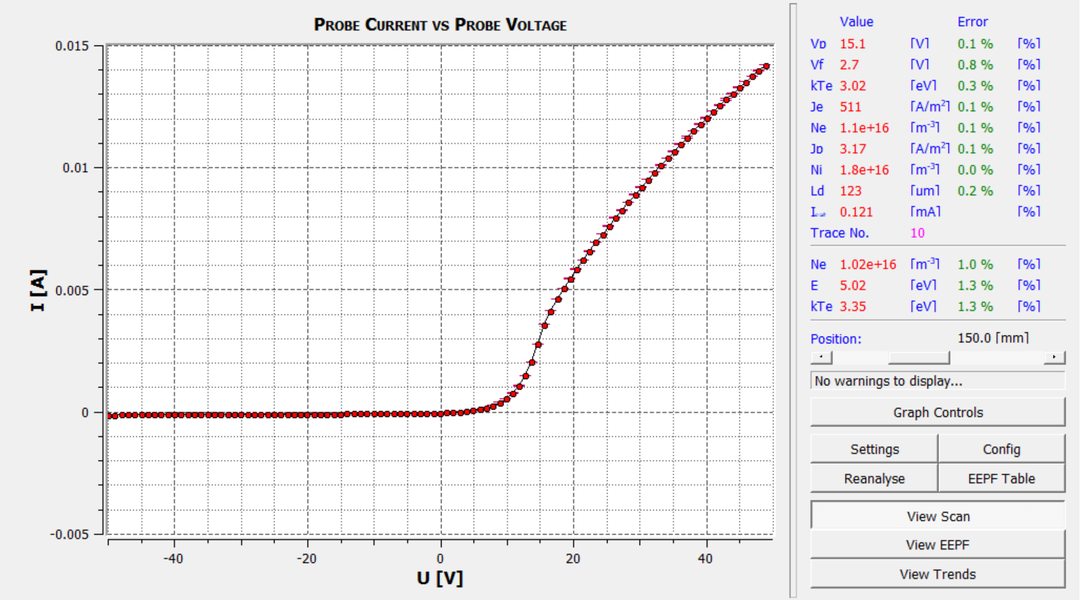
$$e = \frac{I(V_p)}{A_p}\sqrt{\frac{2\pi m_e}{e^2 kT_e}} \qquad (12)$$

Ion flux:

$$I_0 = \frac{I(-80V)}{a_{cyl}(-X)^{b_{cyl}}\left(1 + \frac{r_p}{\lambda_D}\frac{a_{sph}}{a_{cyl}}(-X)^{\Delta b}\right)\gamma_1\gamma_2} \qquad (13)$$

Ion Density:

$$n_i = \frac{I_0}{A_p}\sqrt{\frac{2\pi m_i}{e^2 kT_e}} \qquad (14)$$



	Value		Error	
Vp	15.1	[V]	0.1 %	[%]
Vf	2.7	[V]	0.8 %	[%]
kTe	3.02	[eV]	0.3 %	[%]
Je	511	$[\mathrm{A/m^2}]$	0.1 %	[%]
Ne	1.1e+16	$[\mathrm{m^{-3}}]$	0.1 %	[%]
Jp	3.17	$[\mathrm{A/m^2}]$	0.1 %	[%]
Ni	1.8e+16	$[\mathrm{m^{-3}}]$	0.0 %	[%]
Ld	123	[um]	0.2 %	[%]
I	0.121	[mA]		[%]
Trace No.		10		
Ne	1.02e+16	$[\mathrm{m^{-3}}]$	1.0 %	[%]
E	5.02	[eV]	1.3 %	[%]
kTe	3.35	[eV]	1.3 %	[%]

Position: 150.0 [mm]

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Single Probe: EEPF Equations

Druyvesten Equation

$$n(\varepsilon) = n_e\, f(\varepsilon) = \frac{2\, I''}{e\, A_p}\sqrt{\frac{2m_e}{e}} \qquad (15)$$

Electron Density (from EEPF Characteristic):

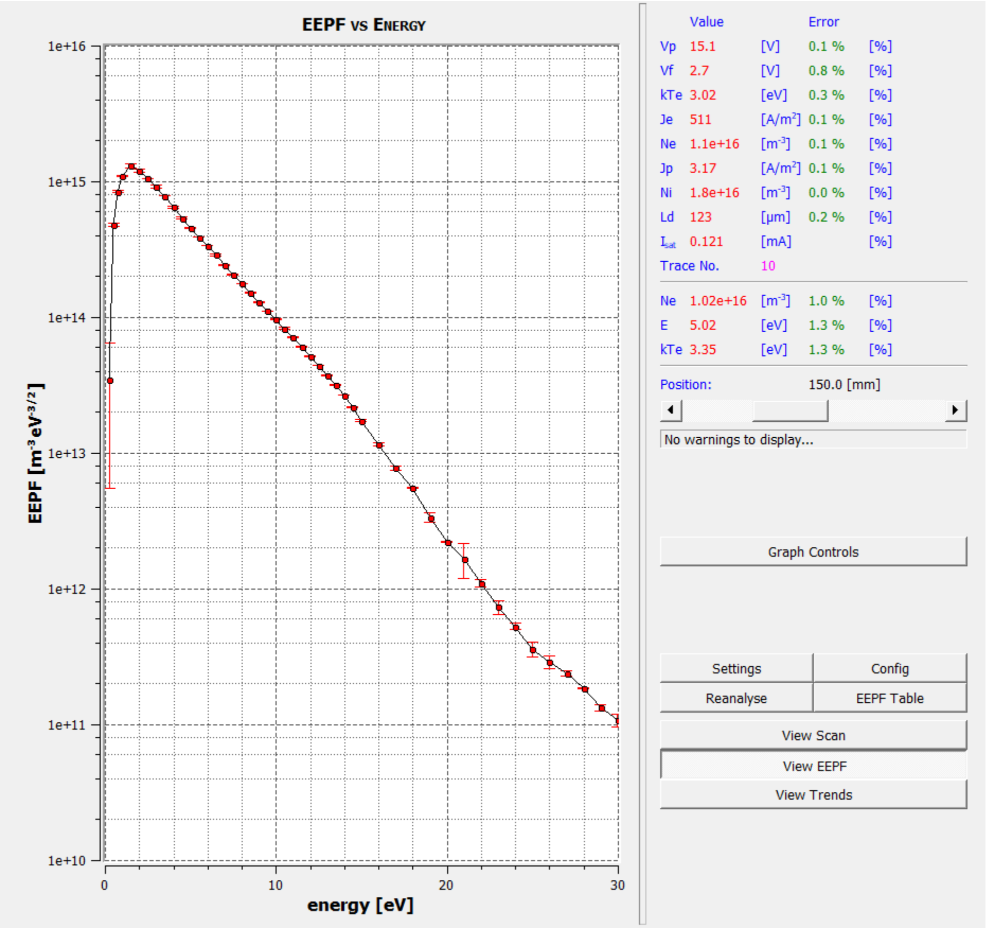
$$n_e = \int_0^{\varepsilon_{max}} n(\varepsilon)\, d\varepsilon \qquad (16)$$

Average Electron Energy:

$$\langle\varepsilon\rangle = \int_0^{\varepsilon_{max}} \varepsilon\, n(\varepsilon)\, d\varepsilon \qquad (17)$$

Electron temperature (from EEPF Characteristic):

$$kT_e = \frac{2}{3}\langle\varepsilon\rangle \qquad (18)$$



	Value		Error	
Vp	15.1	[V]	0.1 %	[%]
Vf	2.7	[V]	0.8 %	[%]
kTe	3.02	[eV]	0.3 %	[%]
Je	511	[A/m²]	0.1 %	[%]
Ne	1.1e+16	[m⁻³]	0.1 %	[%]
Jp	3.17	[A/m²]	0.1 %	[%]
Ni	1.8e+16	[m⁻³]	0.0 %	[%]
Ld	123	[µm]	0.2 %	[%]
I_{sat}	0.121	[mA]		[%]
Trace No.		10		
Ne	1.02e+16	[m⁻³]	1.0 %	[%]
E	5.02	[eV]	1.3 %	[%]
kTe	3.35	[eV]	1.3 %	[%]

Position: 150.0 [mm]

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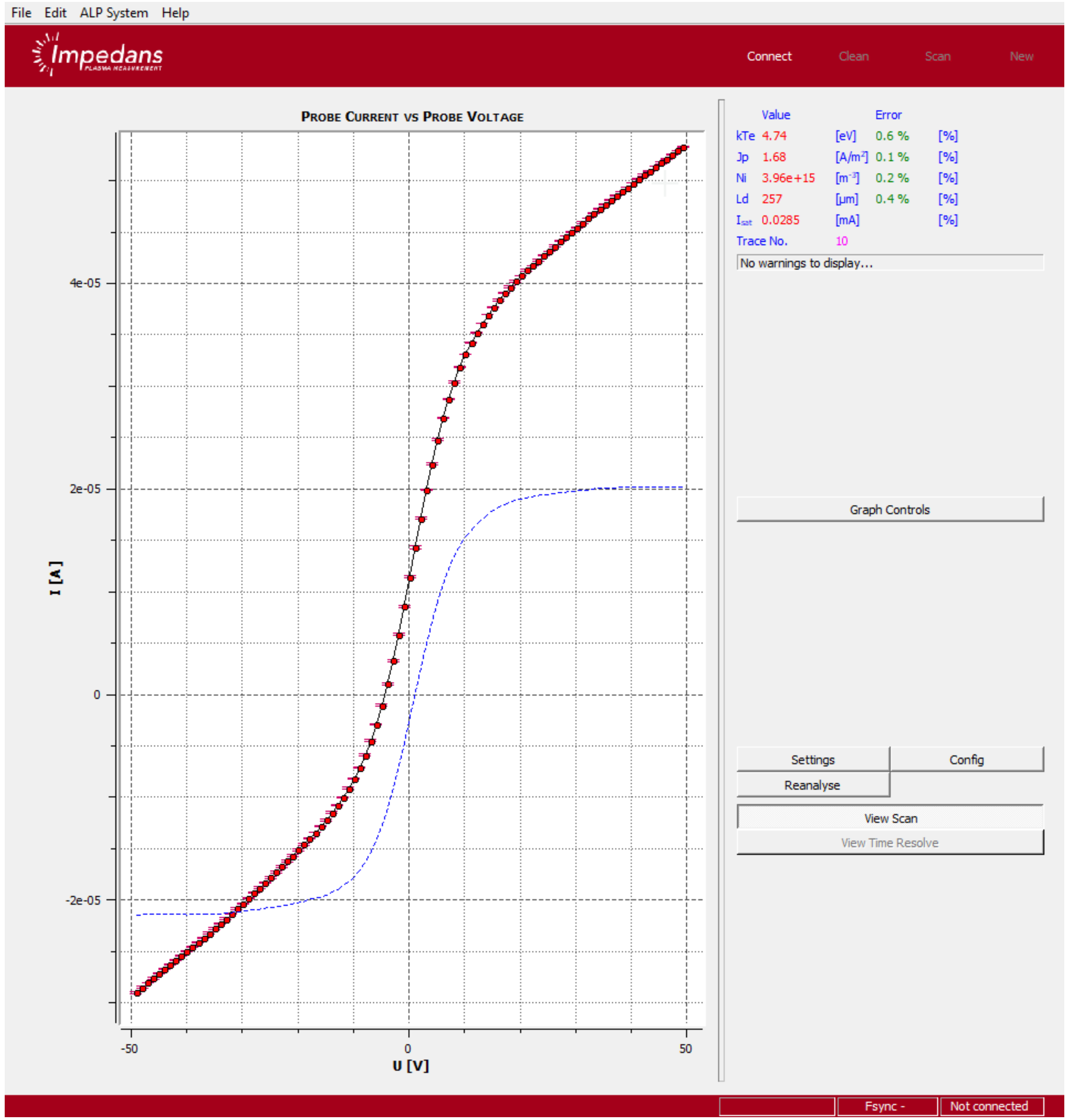
Double Probe: Plasma Parameter Equations

Electron Temperature:

$$\frac{eV}{kT_e} = 2\tanh^{-1}\left(\frac{I_{corrected}}{I_{i,sat}}\right) \qquad (19)$$

Ion Density:

$$n_i = \frac{I_{i,sat}}{A}\sqrt{\frac{2\pi m_i}{e^2 kT_e}} \qquad (20)$$



	Value		Error	
kTe	4.74	[eV]	0.6 %	[%]
Jp	1.68	[A/m²]	0.1 %	[%]
Ni	3.96e+15	[m⁻³]	0.2 %	[%]
Ld	257	[µm]	0.4 %	[%]
I_{sat}	0.0285	[mA]		[%]
Trace No.		10		

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