International Atomic Energy Agency

4th IAEA Technical Meeting on

Negative Ion Based Neutral Injectors,

Padova, Italy May 2005

International Atomic Energy Agency

Measurement of the Electron Energy Distribution Function by Langmuir Probe in an ITER like Hydrogen Negative Ion Source

[1]B. Crowley, [1]D. Homfray, [1]S.J. Cox, [2]D. Boilson, [3]H P L de Esch and [3]R.S. Hemsworth

1.Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon,. OX14 3DB, UK.
2. Association Euratom/DCU, Dublin City University, Dublin 9, Ireland
3. Association Euratom-CEA, CEA Cadarache, F-13108, St. Paul lez Durance, France

The development of a high yield H^- (or D^-) ion source capable of long pulse operation is an essential step towards the realisation of a neutral beam heating system for ITER.

In Cadarache, development on negative ion sources is being carried out on the KAMABOKO III ion source

Outline of Presentation

Introduction

Background

Experimental Method

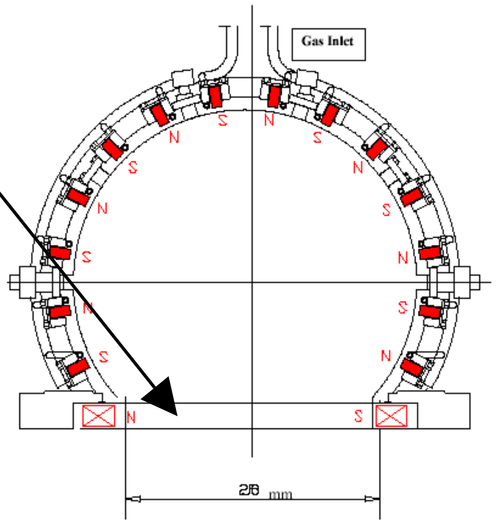
Results

Conclusions

The filter field keeps the electron temperature at the extraction grid low in order to minimise the destruction of H- ions through the process of electron detachment ($e+H^{-}\rightarrow e+H+e$). The cross section for this process increases by 3 orders of magnitude over the electron energy range from 1 to 10 eV. Hence for optimisation of the source it is important to know the electron temperature.

The KAMABOKO III Ion source

an ITER-like source,
i.e. a
Caesiated,
Filamented,
Multi-pole
Arc Discharge Source



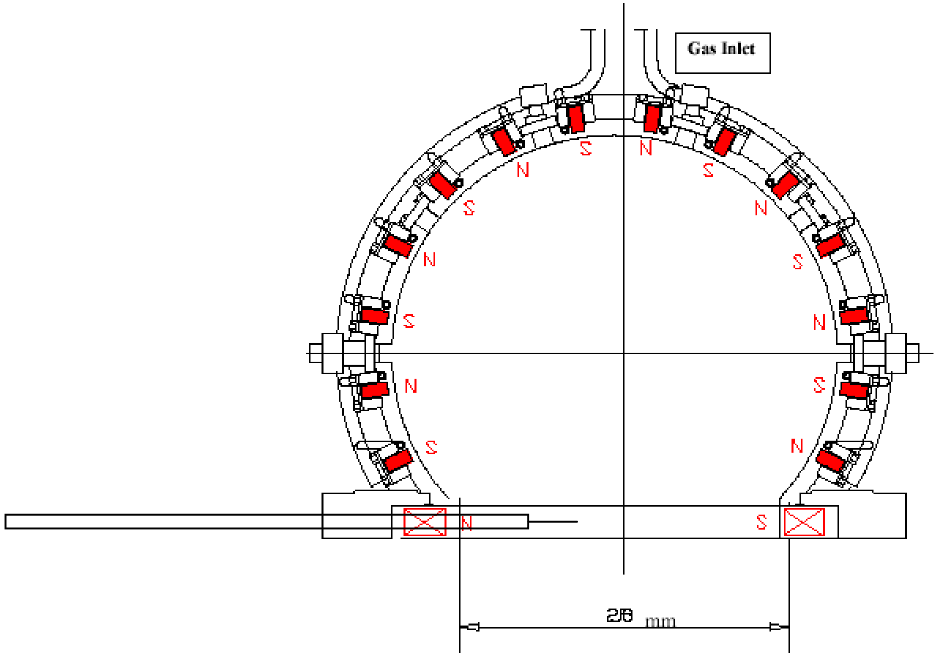
To this end a Langmuir probe is used to measure the plasma parameters (T_e, n_e and V_p) in front of the extraction grid.

Langmuir Probe

W Tip

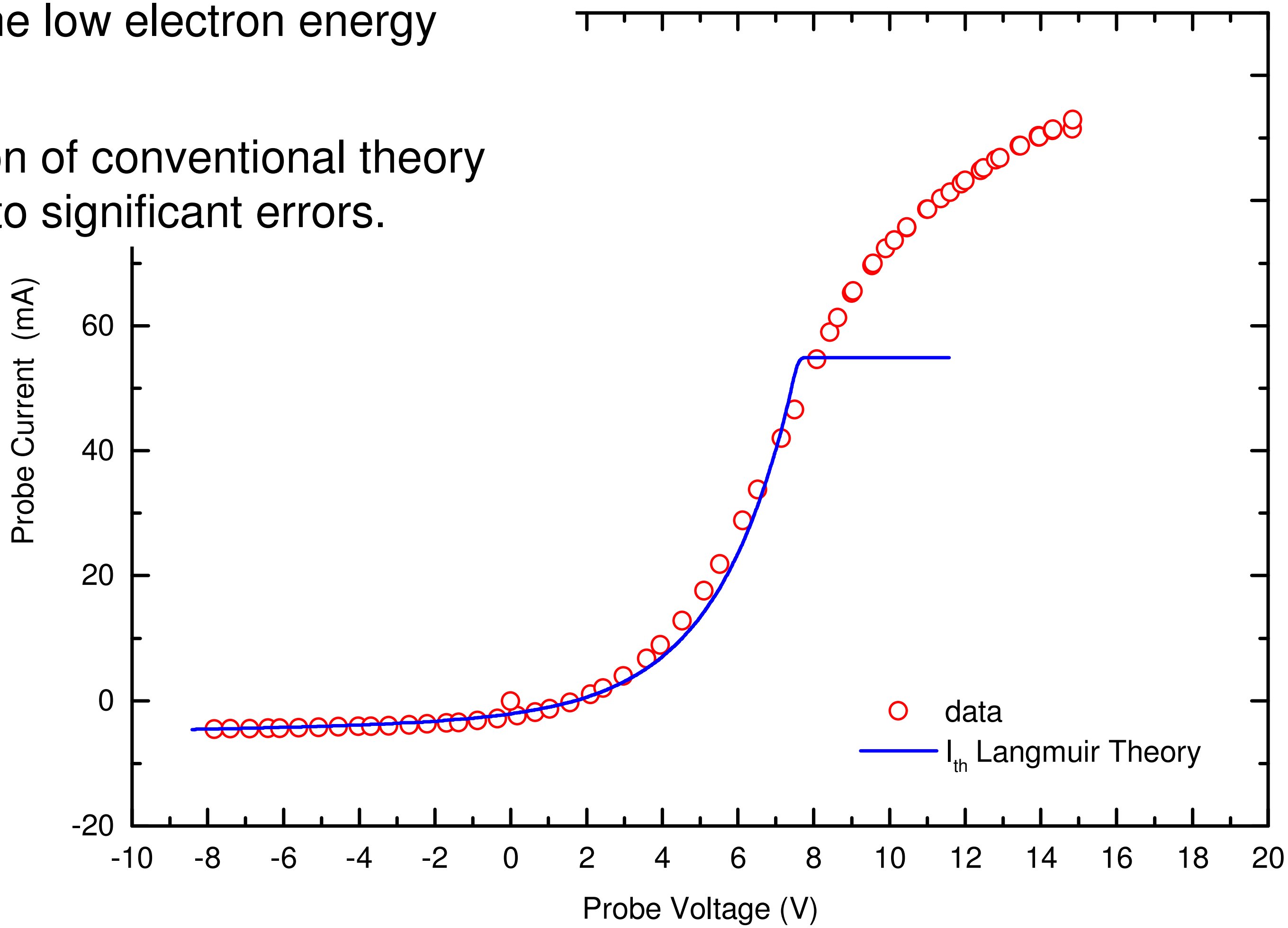
L=5 mm

R=50 μm



Electron energy distribution function (EEDF) is generally non-Maxwellian even at the low electron energy range

Application of conventional theory can lead to significant errors.



The Druyvesteyn extension of the Langmuir and Mott-Smith probe theory allows the determination of the electron energy spectrum. Druyvesteyn shows that the EEDF may be found from the expression,

$$N(\in) = \frac{2}{Ae}\left(\frac{2m\in}{e}\right)^{\frac{1}{2}}\frac{d^2I}{dV^2}$$

and the associated electron energy probability function EEPF is found from

$$P(\in) = \frac{2}{Ae}\left(\frac{2m}{e}\right)^{\frac{1}{2}}\frac{d^2I}{dV^2}$$

The electron density, n_e, is obtained from the integral of $P(\in)$.

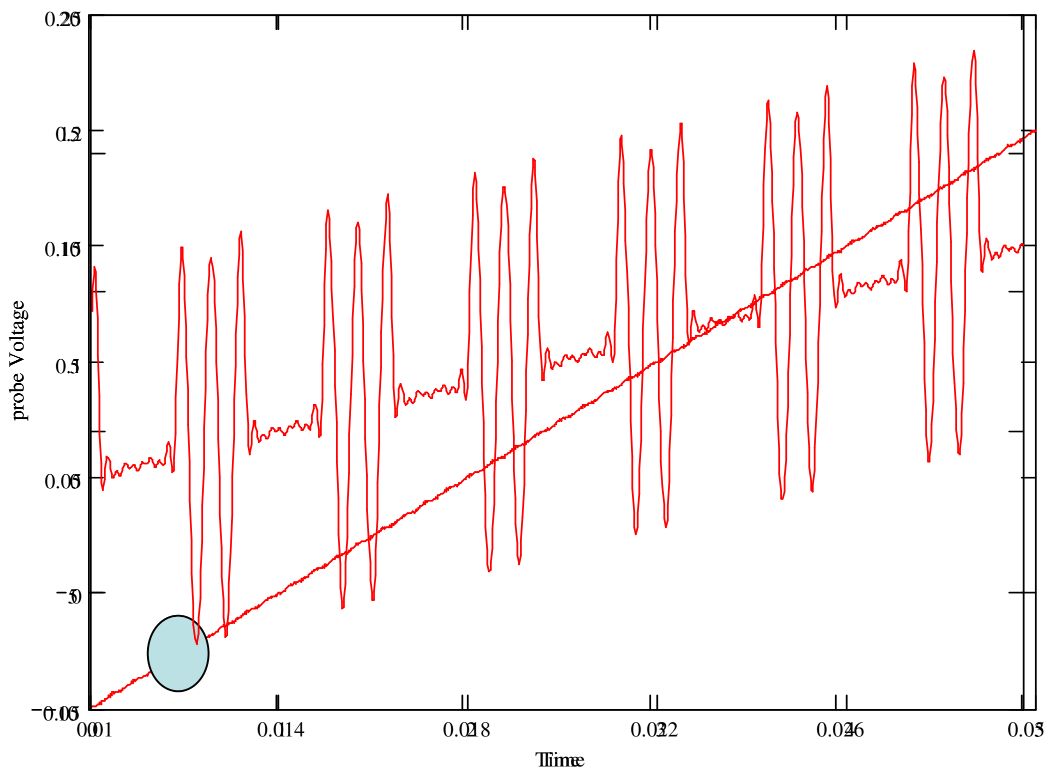
$$n_e = \int_0^\infty P(\in) d\in$$

In the case of a non-Maxwellian electron energy distribution the electron temperature can be thought of as an effective electron temperature defined as,

$$T_{eff} = \frac{2}{3}\langle \in \rangle = \frac{2}{3n_e}\int_0^\infty \in P(\in) d\in$$

Determining the second derivative numerically from the probe data is noisy and prone to errors

To avoid such doubt we have developed a probe system based on the **Boyd and Twiddy** method.



The Boyd-Twiddy Method

Instead of the usual smooth ramp voltage applied to the probe. A modulated ac voltage (e_m) is superimposed on the probe voltage *V.*

The superimopsed voltage can be represented as.

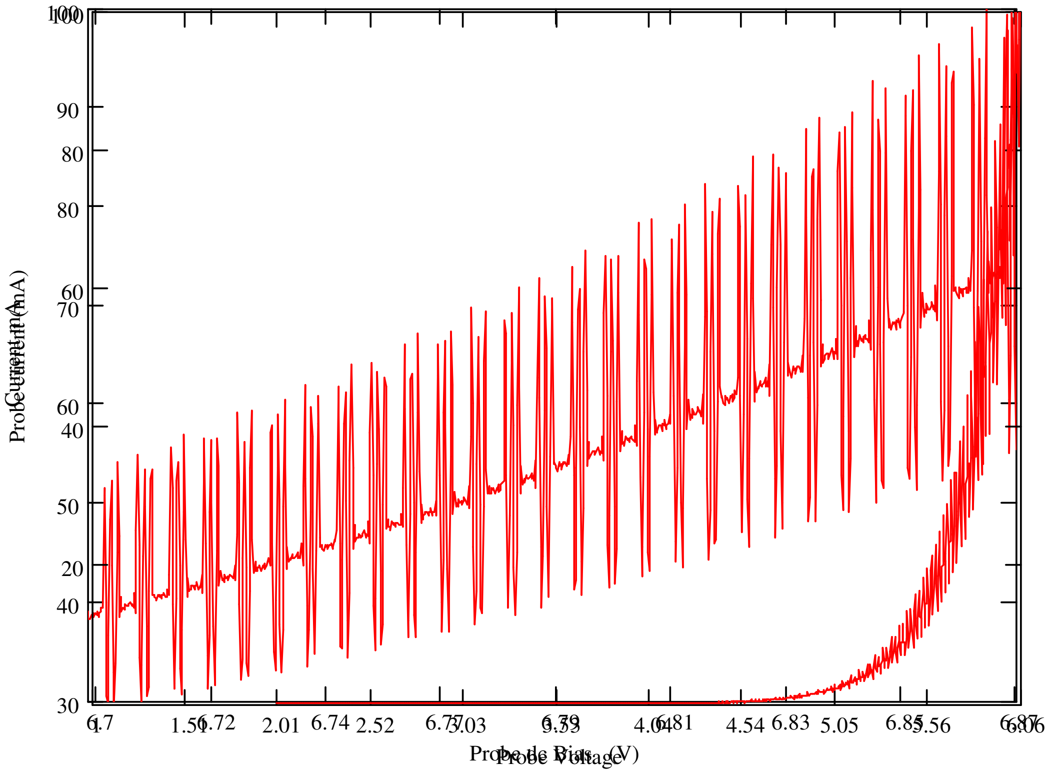
$$e_m = E\left[\frac{1}{2} + \frac{2}{\pi}(\cos pt - \frac{1}{3}\cos 3pt + ..., etc)\right]\cos \omega t$$

Where ω is the carrier frequency and *p* is the modulation frequency

UKAEA Fusion

International Atomic Energy Agency

cea



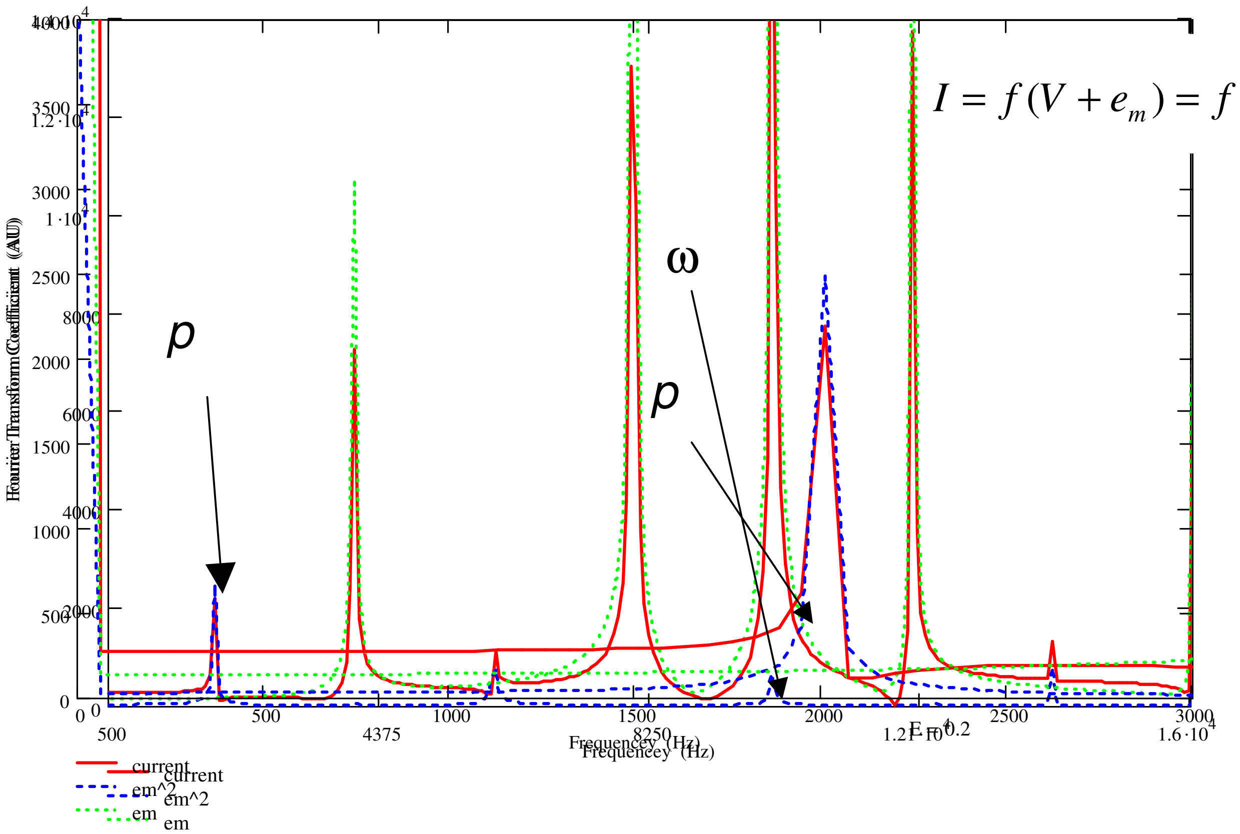
The resultant current drawn by the probe is a function of the probe voltage V plus the modulated signal e_m Langmuir probe trace

$$I = f(V + e_m)$$

By Taylor's Theorem the probe current can be expanded,

$$I = f(V + e_m) = f(V) + e_m f'(V) + \frac{e_m^2}{2!} f''(V).....$$

Frequency Spectrum of the Probe Current



$$I = f(V + e_m) = f(V) + e_m f'(V) + \frac{e_m^{\,2}}{2!} f''(V).....$$

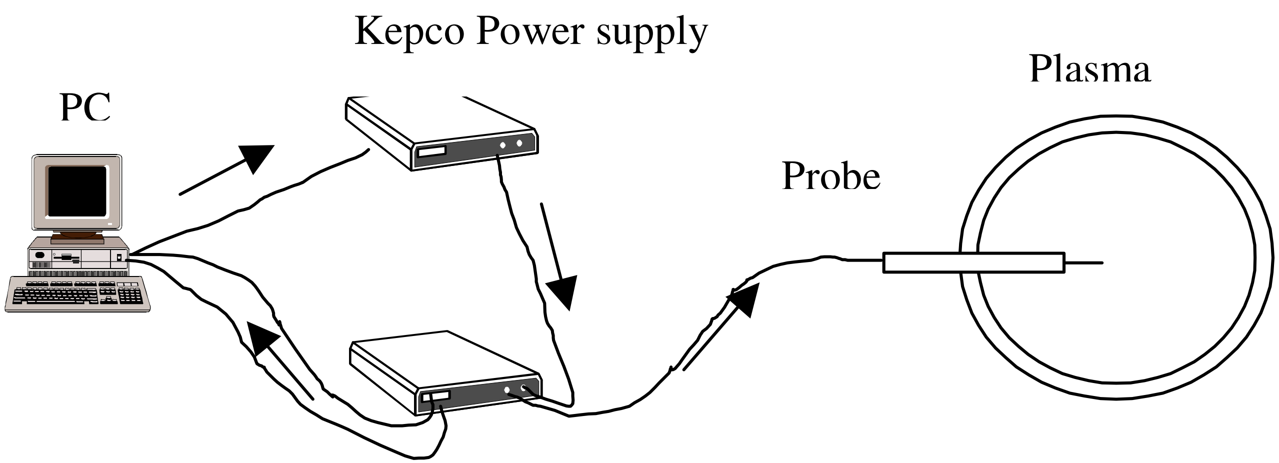
The component of current measured at frequency *p* receives contributions only from even-order derivatives provided that *ω* is not an even multiple of *p*. and is given by,

$$i_p = \left[\frac{E^2}{2!}\frac{1}{\pi} f^{''}(V) + \frac{E^4}{4!}\frac{3}{8}\left(\frac{1}{4} + \frac{1}{\pi^2}\right) f^{''''}(V) + ...etc \right] \cos pt$$

Terms involving the fourth and higher order derivatives can be neglected, hence the second derivative may be obtained from a direct measurement of i_p. In practical units the EEDF is given by.

$$N(\in) = \frac{8\pi}{A}\left(\frac{m\in}{e^3}\right)^{\frac{1}{2}} \frac{i_p(rms)}{E^2} \times \mathrm{eV}^{-1}\,\mathrm{cm}^{-3}$$

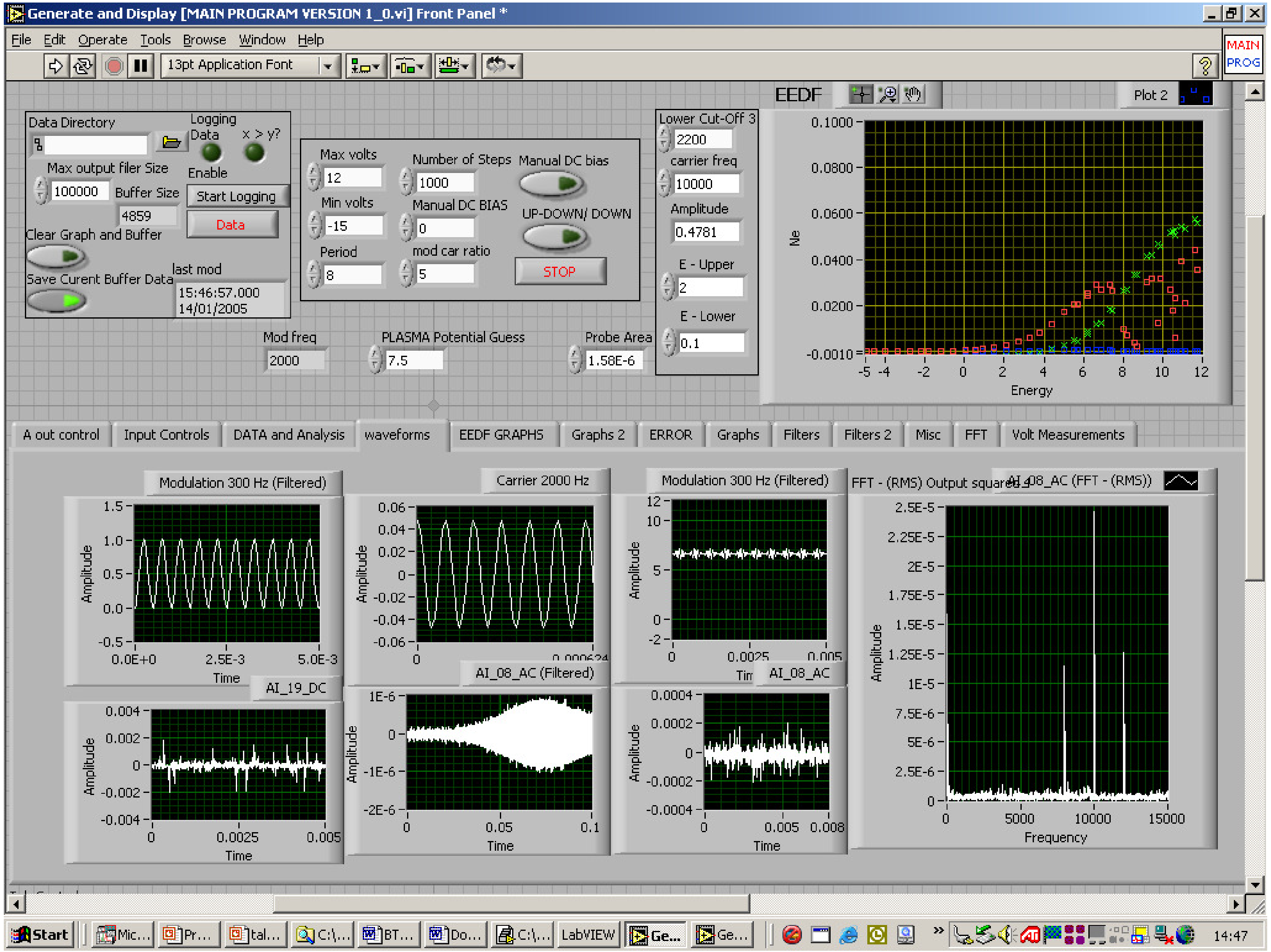
Experimental Set-up



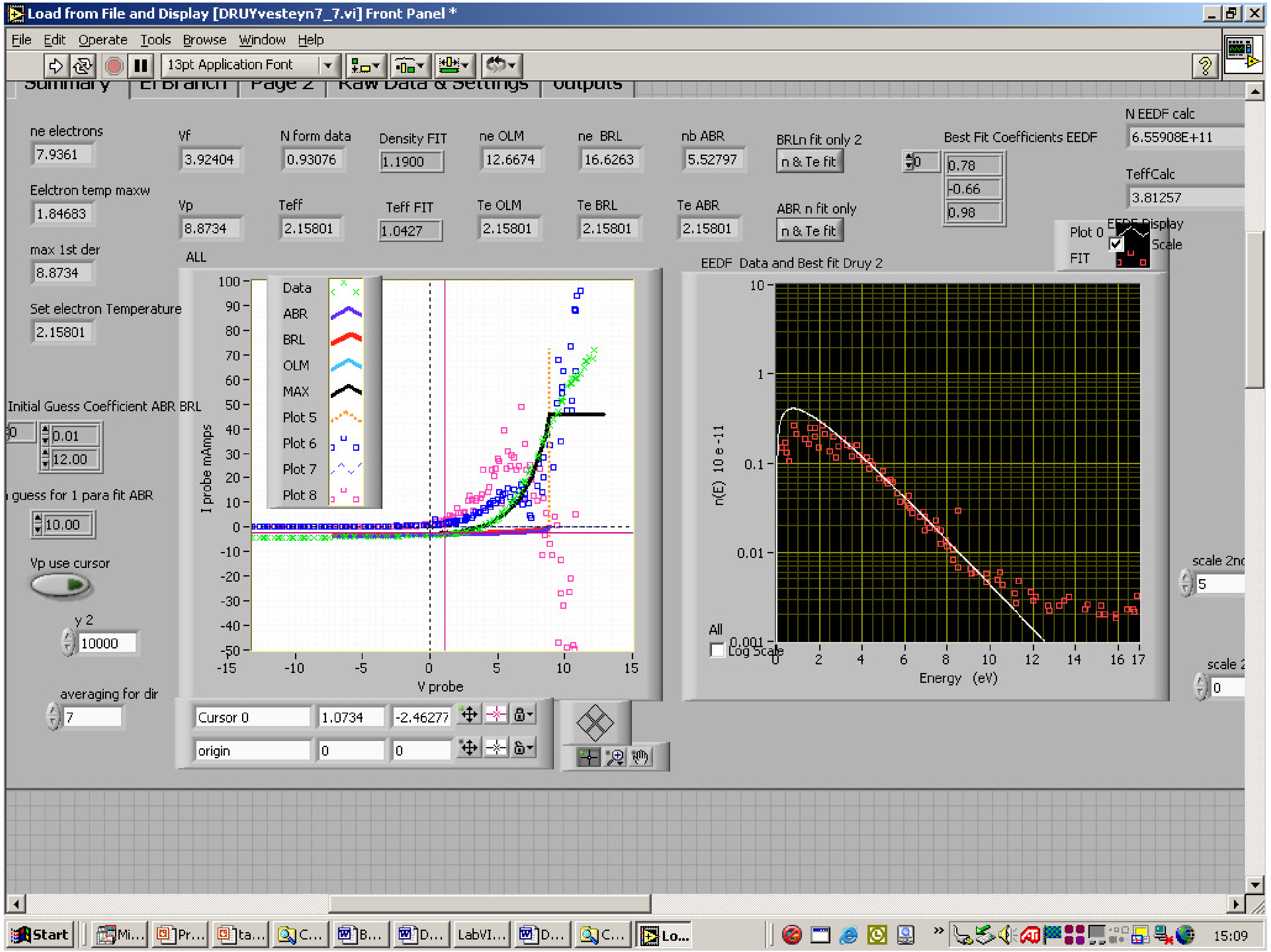
Hardware

- •NI PCI M DAQ 16 bit 1.25 M samples s^{-1}
- •KEPCO +/- 100 V Bipolar Operational Power Amplifier 20 kHz Bandwdth
- •UAAA isolation Amplifier

International Atomic Energy Agency



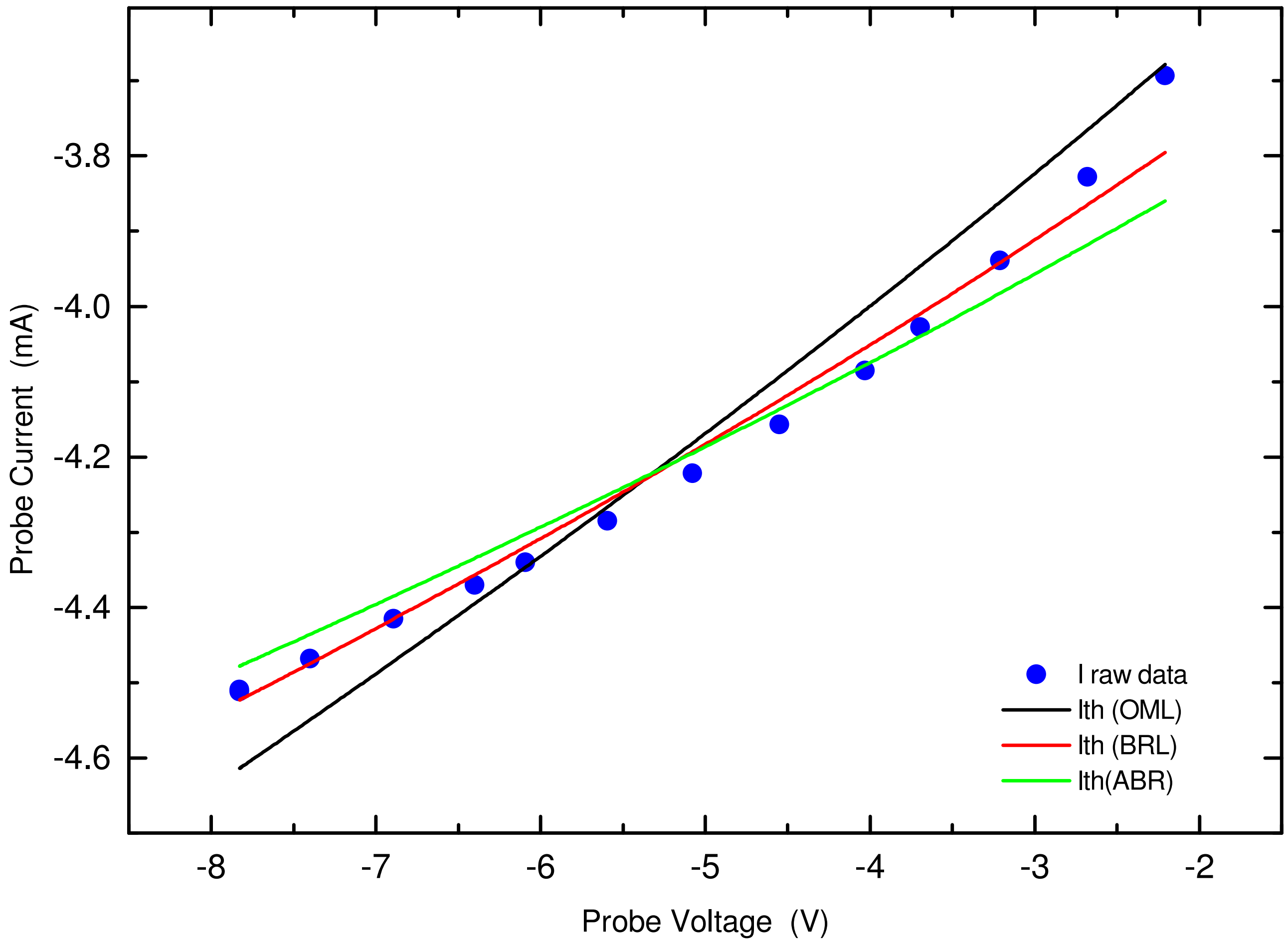
Screen shot of BT data acquisition program

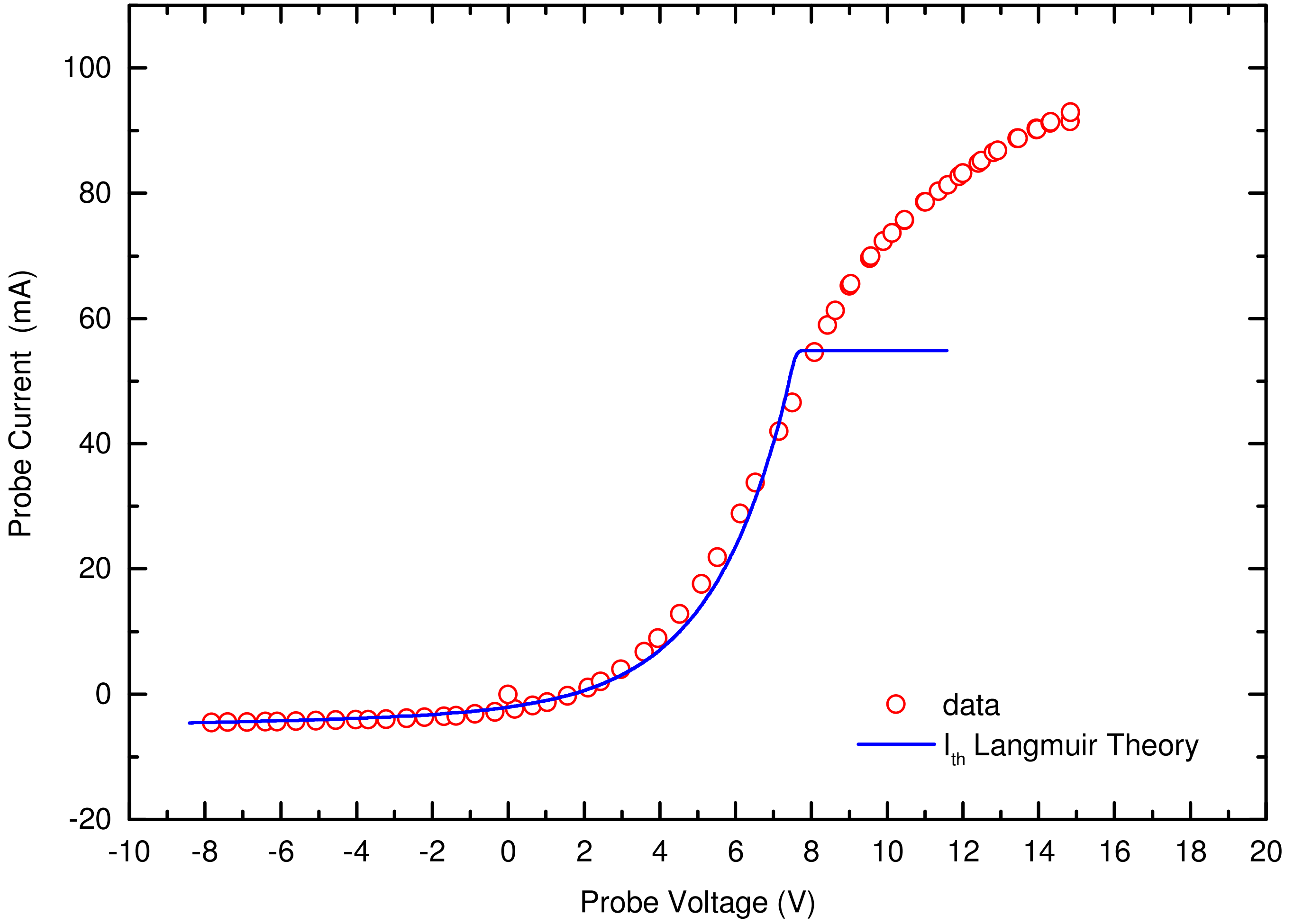


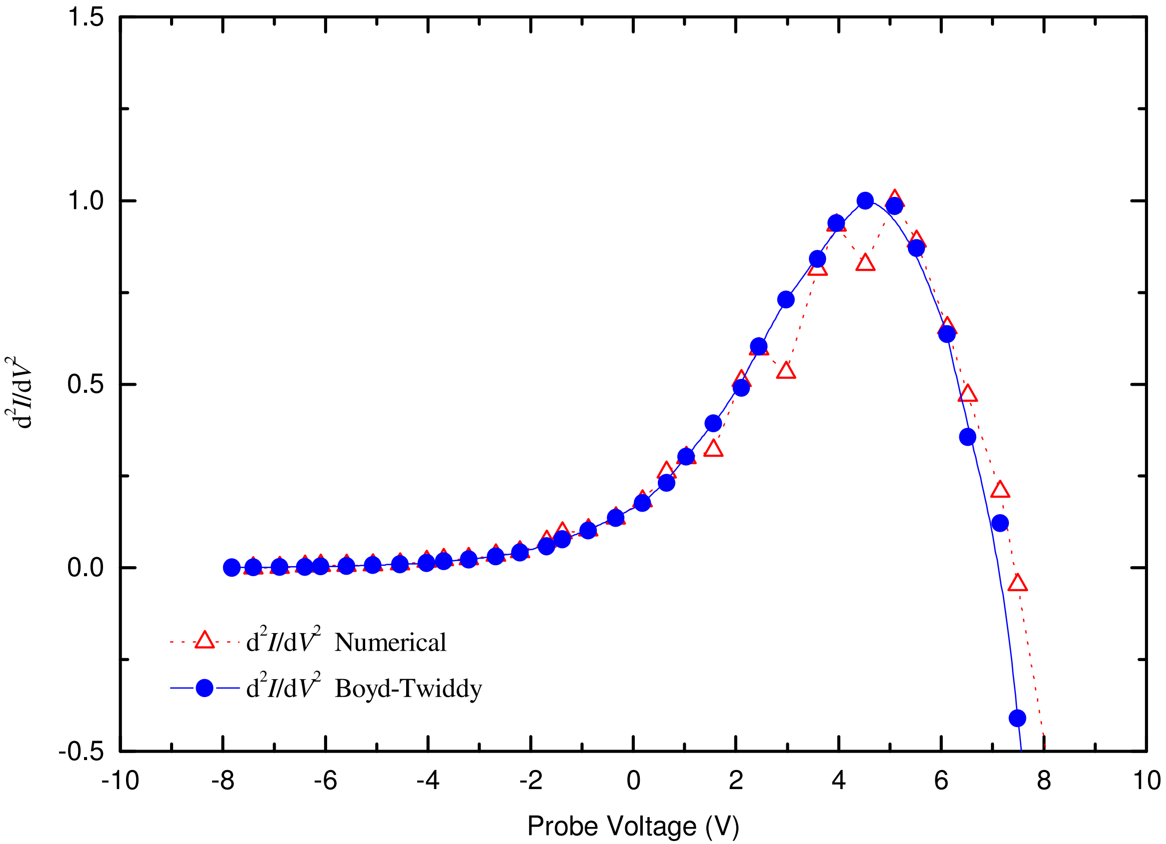
Screen shot of BT data analysis program

The traditional Langmuir probe *I-V* characteristic trace is analysed using the following methods.

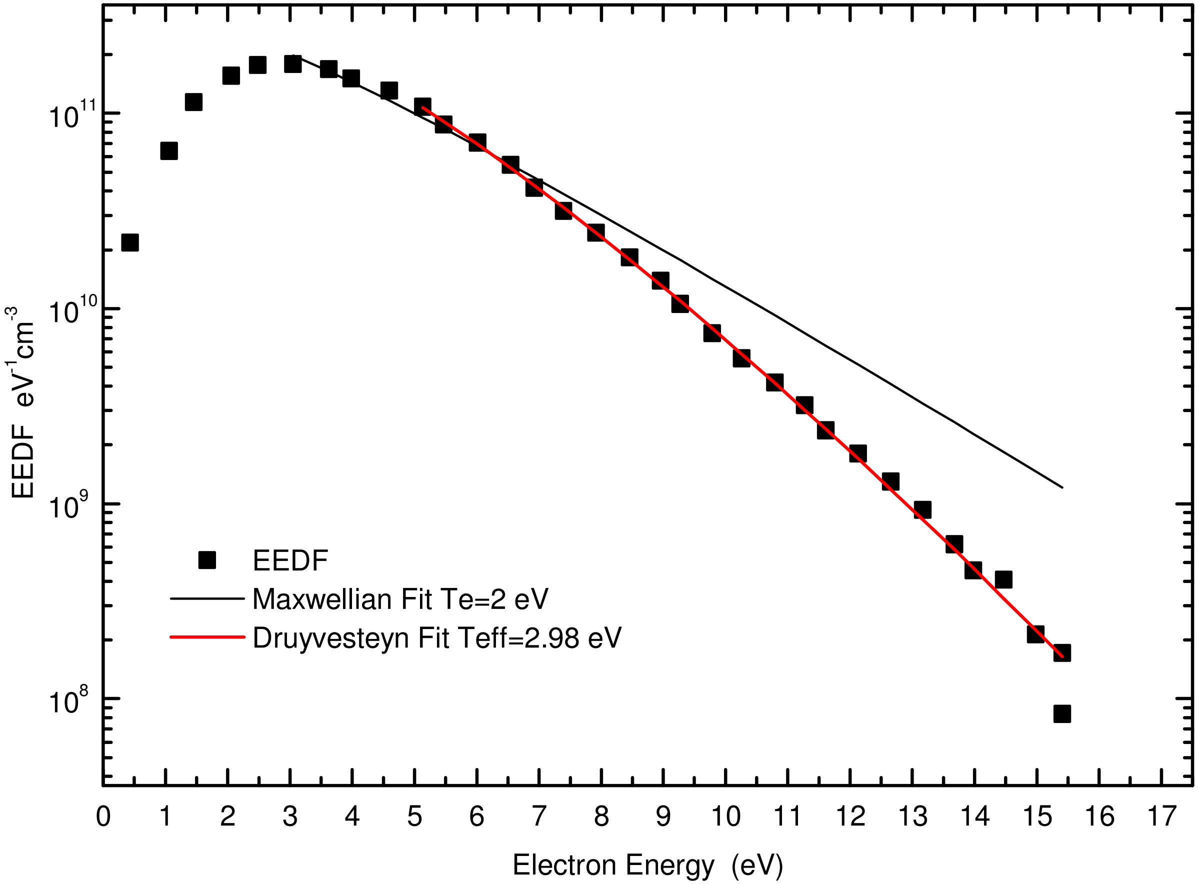
- **The Orbital Motion Limited (OML) theory of ion collection.**
- **The Allen-Boyd-Reynolds (ABR) radial motion theory of ion collection .**
- **Bernstein-Rabinowitz-Laframboise (BRL) theory of ion collection.**
- **Classical Langmuir-Mott Smith (LMS) theory for electron collection.**


-3.8
-4.0
-4.2
-4.4
-4.6
Probe Current (mA)
-8
-7
-6
-5
-4
-3
-2
Probe Voltage (V)
I raw data
Ith (OML)
Ith (BRL)
Ith(ABR)


Probe Current (mA)
Probe Voltage (V)
100
80
60
40
20
0
-20
-10
-8
-6
-4
-2
0
2
4
6
8
10
12
14
16
18
20
data
I_{th} Langmuir Theory



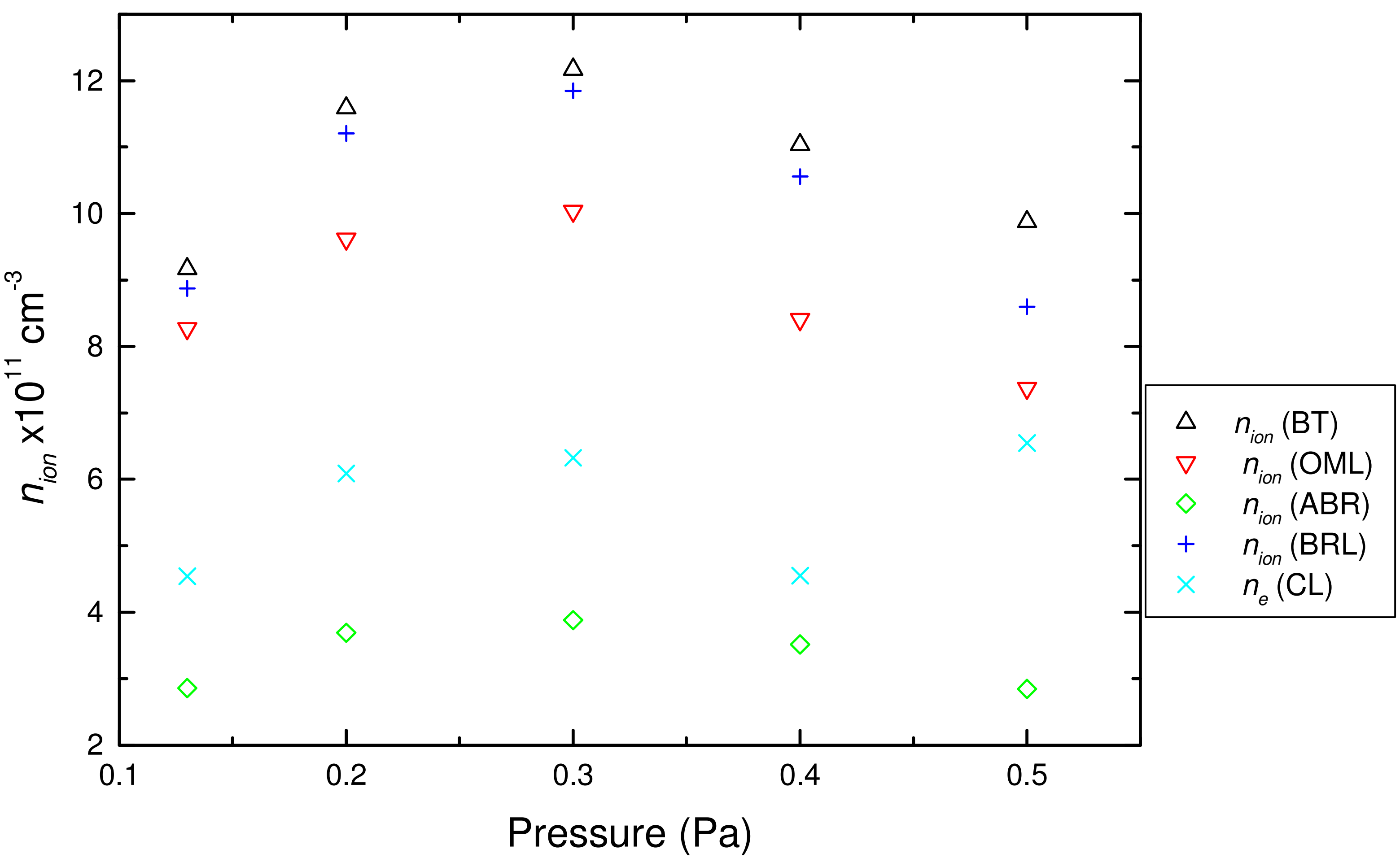
2nd derivative of the IV curve showing numerical and BT method. Measurement taken at the centre of the discharge with arc power is 47 kW and the gas pressure 0.3 Pa.

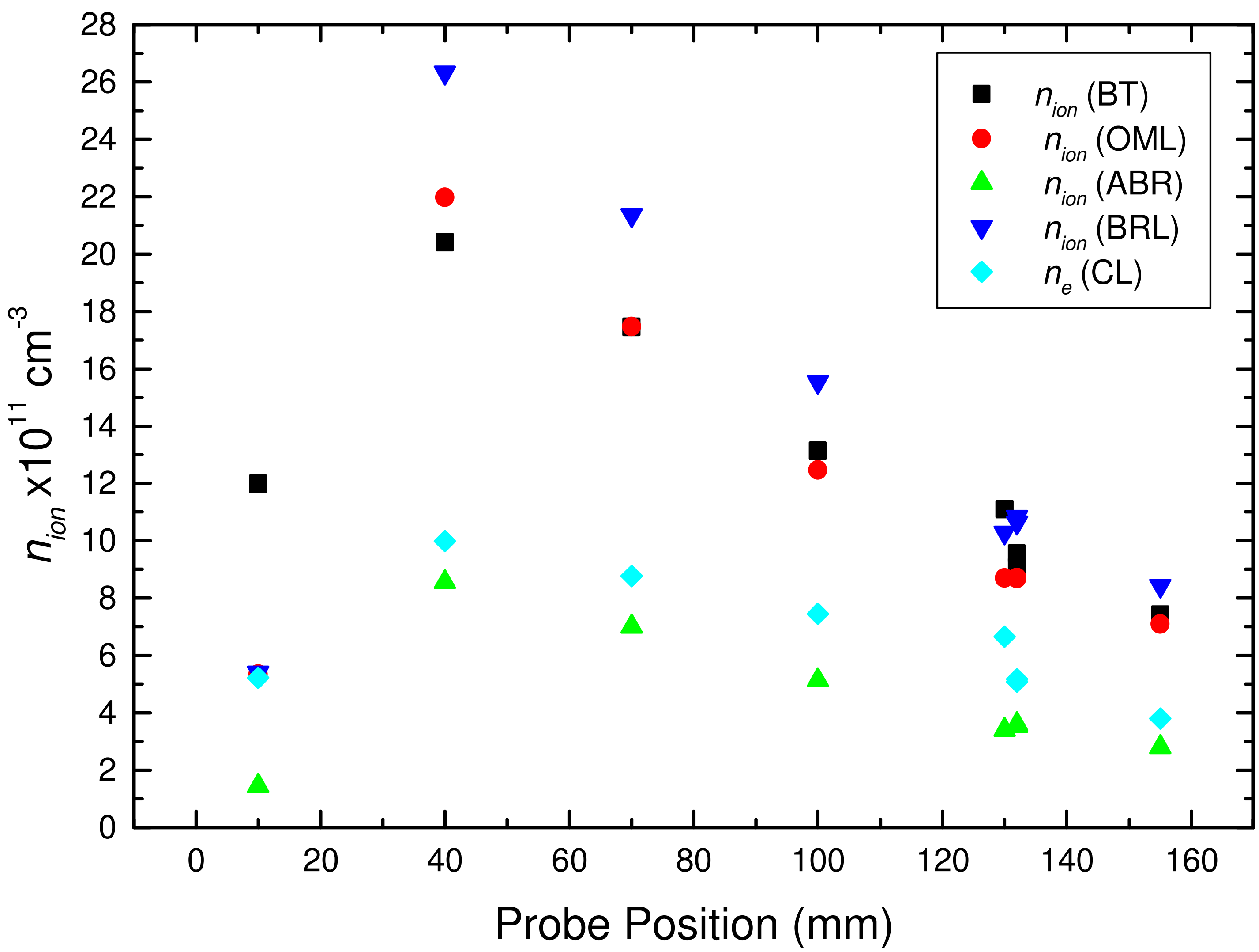


Plot of EEDF with fitted Maxwellian and Druyvesteyn distributions. Measurement taken at the centre of the discharge with arc power is 47 kW and the gas pressure 0.3 Pa.

V_p	V_f	T_e (LMS)	T_{eff} (BT)	n_e (BT)	n_e (LMS)	n_e (OML)	n_e (ABR)	n_e (BRL)
V	V	eV	eV	cm^{-3}	cm^{-3}	cm^{-3}	cm^{-3}	cm^{-3}
7.58	1.56	2.05	2.98	1.6×10^{12}	9×10^{11}	1.5×10^{12}	5.5×10^{11}	1.7×10^{12}

Table 1. Summary of results from IV curve


12
10
8
6
4
2
0.1
0.2
0.3
0.4
0.5
n_{ion} x10^{11} cm^{-3}
Pressure (Pa)
n_{ion} (BT)
n_{ion} (OML)
n_{ion} (ABR)
n_{ion} (BRL)
n_e (CL)



n_{ion} x10^{11} cm^{-3}
Probe Position (mm)
n_{ion} (BT)
n_{ion} (OML)
n_{ion} (ABR)
n_{ion} (BRL)
n_e (CL)

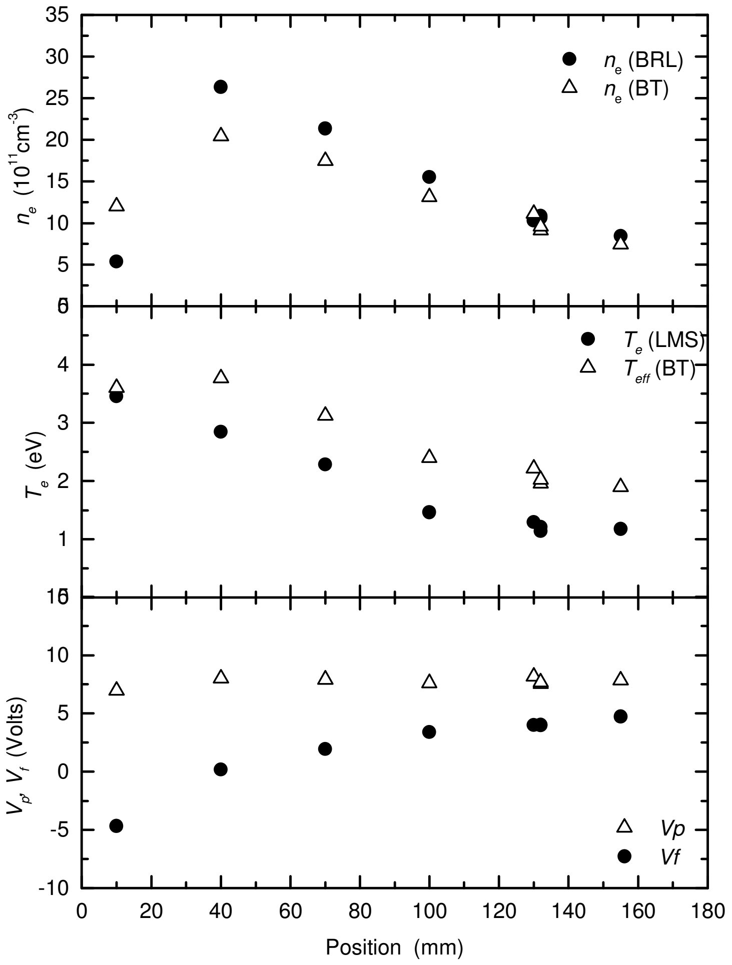
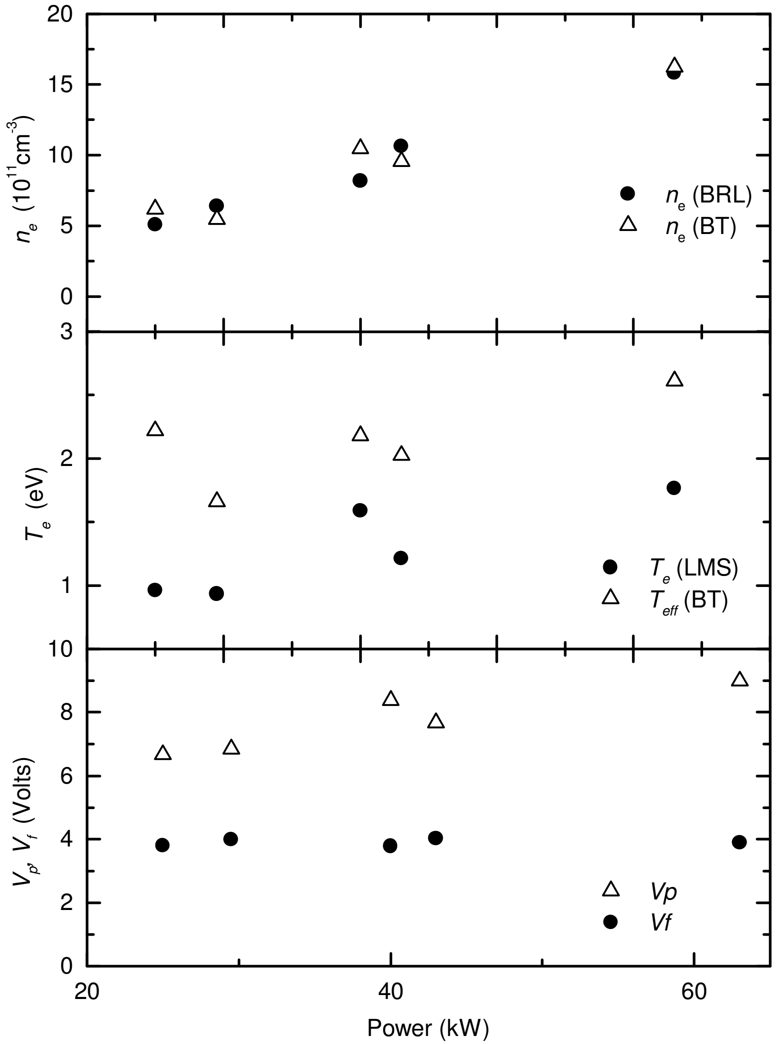


Figure 7 Plasma parameters as a function of position from the edge to the centre of the source.



Plasma parameters as a function of Power

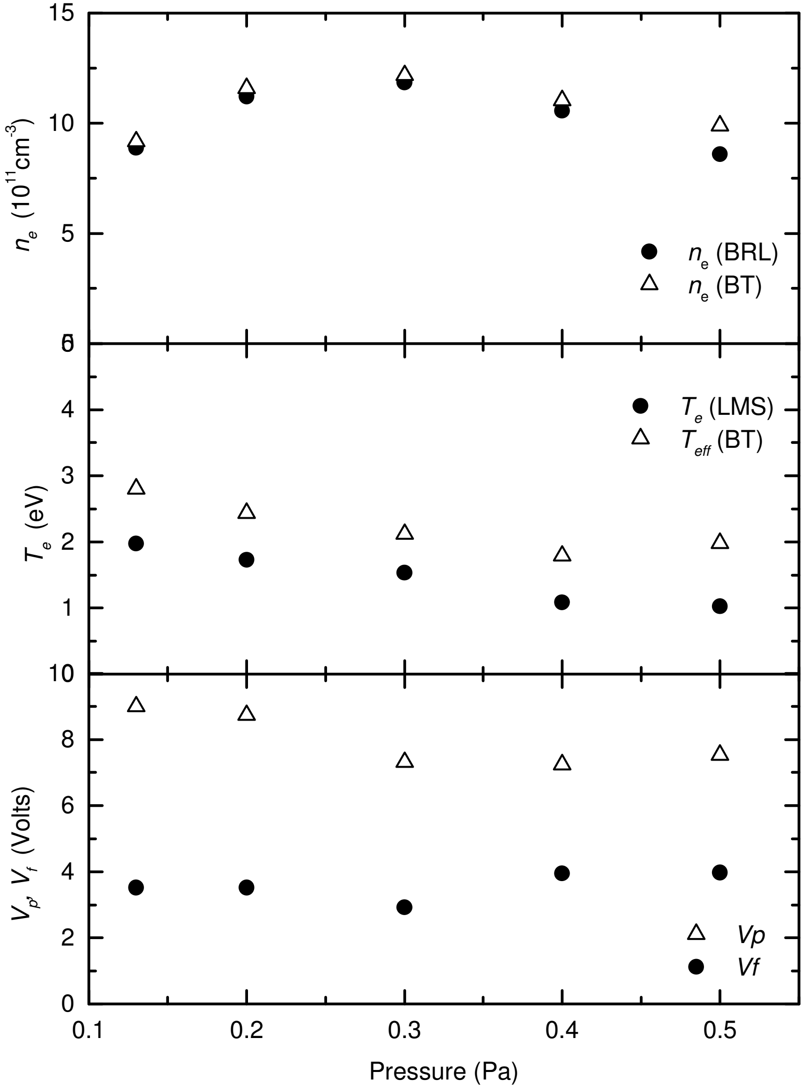


Figure 8 Plasma parameters as a function of Pressure

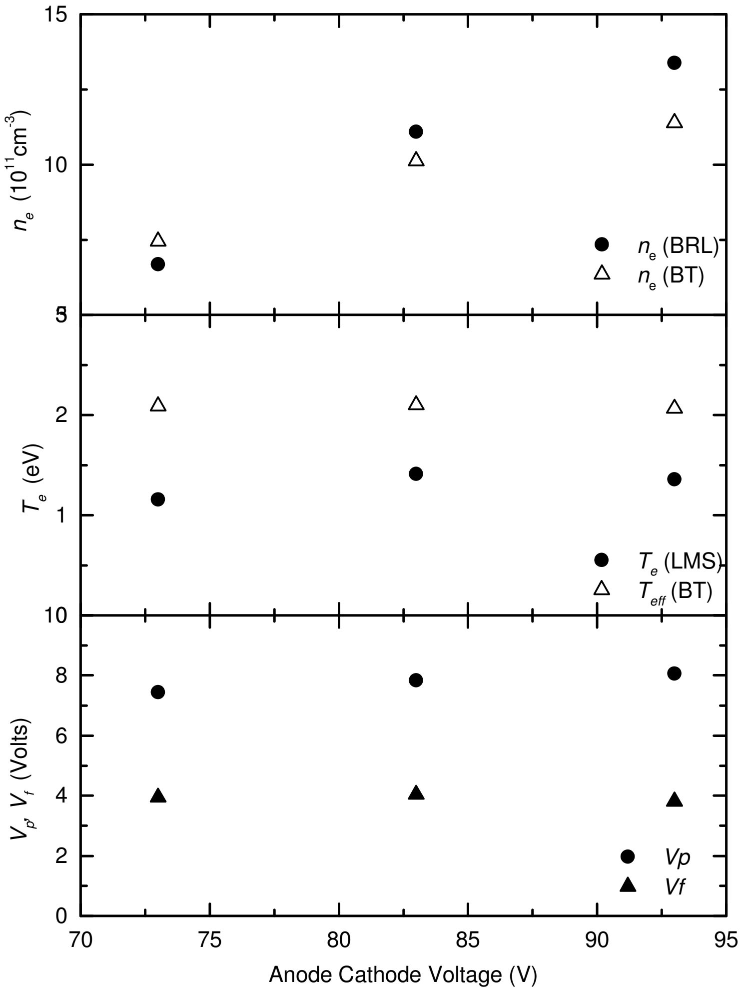


Figure 10 Plasma parameters as a function of Anode-Cathode Voltage

CONCLUSIONS

A Langmuir probe system capable of directly measuring the 2nd derivative of the *I-V* trace has been developed and tested in the KAMABOKO III source.
The probe system is also capable of analysing the *I-V* trace using a variety of common procedures.

Plasma parameters in the KAMABOKO III source were determined and the EEDF was found to be non-Maxwellian and the electron temperature was found to be higher than the inferred Maxwellian temperature.

The EEDF as determined by both numerical differentiation and the direct 2nd derivative (Boyd-Twiddy) method have been compared. Both methods gave a similar form for the EEDF but the form of the numerical method depended on the smoothing method employed.

Since the degree of departure of the EEDF from Maxwellian may not be known, measuring the EEDF is the most reliable way to use the Langmuir probe diagnostic.

Measurement of the Electron Energy Distribution Function by Langmuir Probe in an ITER like Hydrogen Negative Ion Source

[1]B. Crowley, [1]D. Homfray, [1]S.J. Cox, [2]D. Boilson, [3]H P L de Esch and [3]R.S. Hemsworth

1.Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon,. OX14 3DB, UK.

2. Association Euratom/DCU, Dublin City University, Dublin 9, Ireland

3. Association Euratom-CEA, CEA Cadarache, F-13108, St. Paul lez Durance, France

Conclusions

A Langmuir probe system capable of directly measuring the 2nd derivative of the *I-V* trace has been developed and tested in the KAMABOKO III source. The probe system is also capable of analysing the *I-V* trace using a variety of common procedures.

Plasma parameters in the KAMABOKO III source were determined and the EEDF was found to be non-Maxwellian and the electron temperature was found to be higher than the inferred Maxwellian temperature.

The EEDF as determined by both numerical differentiation and the direct 2nd derivative (Boyd-Twiddy) method have been compared. Both methods gave a similar form for the EEDF but the form of the numerical method depended on the smoothing method employed.

Since the degree of departure of the EEDF from Maxwellian may not be known, measuring the EEDF is the most reliable way to use the Langmuir probe diagnostic.

A Langmuir probe system capable of directly measuring the 2nd derivative of the *I-V* trace has been developed and tested in the KAMABOKO III source. The probe system is also capable of analysing the *I-V* trace using a variety of common procedures.

Plasma parameters in the KAMABOKO III source were determined and the EEDF was found to be non-Maxwellian and the electron temperature was found to be higher than the inferred Maxwellian temperature.

The EEDF as determined by both numerical differentiation and the direct 2nd derivative (Boyd-Twiddy) method have been compared. Both methods gave a similar form for the EEDF but the form of the numerical method depended on the smoothing method employed.

Since the degree of departure of the EEDF from Maxwellian may not be known, measuring the EEDF is the most reliable way to use the Langmuir probe diagnostic.

Hardware

- NI PCI M DAQ 16 bit 1.25 M samples s^{-1}
- KEPCO +/- 100 V Bipolar Operational Power Amplifier 20 kHz Bandwdth
- UAAA isolation Amplifier

Boyd and Twiddy [1]. The method is to superimpose a modulated ac voltage (*em*) on the probe voltage *V*; the superimposed voltage can be represented as

where E is the peak of the modulated signal, and *p* and *ω* are the frequencies of the modulation and carrier signals respectively.

By Taylor's Theorem the probe current can be expressed as,

The component of current measured at frequency *p* receives contributions only from even-order derivatives provided that *ω* is not a multiple of *p*. and is given by,

Terms involving the fourth and higher order derivatives can be neglected, hence the second derivative may be obtained from a direct measurement of *ip*. In practical units the EEDF is given by.

$$e_m = E\left[\frac{1}{2} + \frac{2}{\pi}(\cos pt - \frac{1}{3}\cos 3pt + ..., etc)\right]\cos \omega t$$

$$I = f(V + e_m) = f(V) + e_m f'(V) + \frac{e_m^{\ 2}}{2!} f''(V).....$$

$$i_p = \left[\frac{E^2}{2!}\frac{1}{\pi} f^{''}(V) + \frac{E^4}{4!}\frac{3}{8}\left(\frac{1}{4} + \frac{1}{\pi^2}\right) f^{''''}(V) + ...etc\right]\cos pt$$

$$N(\in) = \frac{8\pi}{A}\left(\frac{m\in}{e^3}\right)^{\frac{1}{2}} \frac{i_p(rms)}{E^2}$$