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

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Abstract

Determining d^2I/dV^2 from a traditional Langmuir probe trace using numerical techniques is inherently noisy and generally yields poor results. We have developed a Langmuir probe system based on a method first used in the 1950's by Boyd and Twiddy [1]. The system measures the 2nd derivative directly. This paper presents an account of the experimental method, apparatus and software used along with some preliminary results from the KAMABOKO III source including a comparison with conventional probe methods.

Introduction

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 (an ITER-like source, *i.e.* a caesiated, filamented, multi-pole arc discharge source). The system is fully described elsewhere [2,3]. A key feature of the ion source is the separation of the driver region from the extraction region by means of the magnetic filter field. 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. 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. But, the electron energy distribution function (EEDF) in low pressure plasmas is generally non-Maxwellian even at the low electron energy range and application of conventional theory can lead to significant errors. In non-Maxwellian plasmas, the electron temperature can be thought of as an effective electron temperature corresponding to a mean electron energy determined from the integrals of the EEDF. Druyvesteyn [4] shows that the EEDF is proportional to $\sqrt{V}\frac{d^2I}{dV^2}$, where d^2I/dV^2 is the second derivative of the probe current-voltage characteristic.

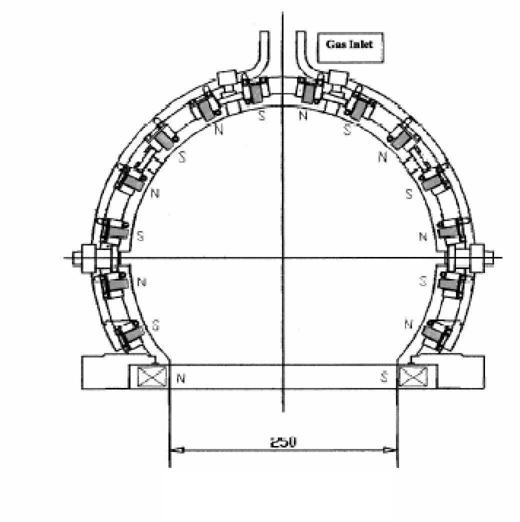


Figure 1 Cross Section of KAMABOKO III Ion Source

Background

Langmuir probes are vital diagnostic tools in the study of low pressure weakly ionised plasmas. Local measurements of various plasma parameters are possible using Langmuir probes making them superior to many other diagnostic techniques. These strongly non-equilibrium plasmas are characterised by an electron temperature that is much higher than the ion or neutral gas temperature. Moreover the electron temperature itself is generally non-Maxwellian, particularly in arc driven systems where the plasma is sustained by primary electrons falling through a potential of approximately 100 volts.

Many probe theories [5,6,7,9] have been developed over the years to determine the plasma parameters from probe traces under various conditions. These theories apply to either ion collection by a probe or electron collection assuming a Maxwellian electron distribution. Analysis of non-Maxwellian plasmas using these techniques yields misleading results [8].

The Druyvesteyn [4] extension of the Langmuir and Mott-Smith probe theory [9] allows the determination of the electron energy spectrum. Druyvesteyn shows that the EEDF may be found from the expression,

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

and the associated electron energy probability function EEPF is found from

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

where $N(\in)$ is the electron concentration, V is the probe voltage, $\in$ is the probe voltage with respect to the plasma potential V_p, ($\in = V_p - V$), A is the probe area, d^2I/dV^2 is the second derivative of the current-voltage characteristic and e and m are the electronic charge and mass.

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

$$n_e = \int_0^\infty P(\in) d\in \qquad \text{Equation 3}$$

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

$$T_{eff} = \frac{2}{3}\langle\in\rangle = \frac{2}{3n_e}\int_0^\infty \in P(\in) d\in \qquad \text{Equation 4}$$

However determining d^2I/dV^2 from a traditional Langmuir probe trace using numerical techniques is inherently noisy and generally yields poor results.

In this paper we present an alternative method first used in the 1950's by Boyd and Twiddy [1]. The method is to superimpose a modulated ac voltage (e_m) on the probe voltage V; the superimposed voltage can be represented as

$$e_m = E\left[\frac{1}{2} + \frac{2}{\pi}(\cos pt - \frac{1}{3}\cos 3pt + ..., etc)\right]\cos\omega t \, , \qquad \text{Equation 5}$$

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,

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

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

$$i_p = \left[\frac{E^2}{2!}\frac{1}{\pi} f''(V) + \frac{E^4}{4!}\frac{3}{8}\left(\frac{1}{4} + \frac{1}{\pi^2}\right) f''''(V) + ...etc\right]\cos pt \qquad \text{Equation 6}$$

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.

$$N(\in) = \frac{8\pi}{A}\left(\frac{m\in}{e^3}\right)^{\frac{1}{2}} \frac{i_p(rms)}{E^2} \mathbf{(eV)^{-1} cm^{-3}} \qquad \text{Equation 7}$$

Experimental Set-up

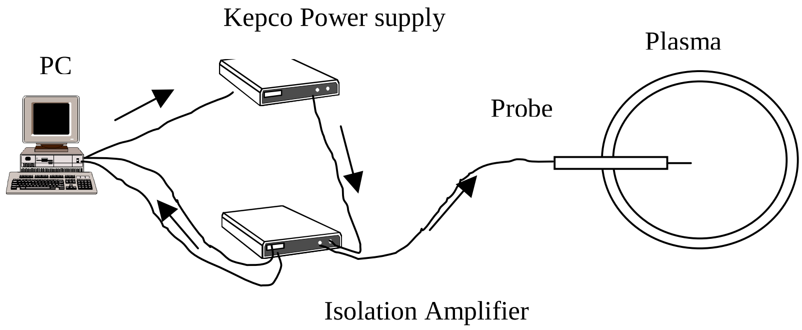


Figure 2. Schematic of Experimental Set-up

Hardware

The cylindrical tungsten probe is 0.5 cm long with radius of 50 μm. The probe is mounted on a ceramic shaft that is housed in a bellows type motorised linear drive mechanism. This allows precise positioning of the probe for spatial scans across the plasma grid.

The controlling PC contains a National Instruments M-series data acquisition card. The card is a 16 bit 2.5 Msamples s^{-1} with 4 analogue output and 16 analogue input channels. Output channels from the card are connected to a KEPCO bipolar operational power supply. The power supply has a voltage range of ±100 V , a current rating of 1 Amp and 20 kHz bandwidth. The output of the power supply is connected to the probe and the current drawn on the probe fed to a 2 channel isolation amplifier. The signal at one channel has its dc component removed before amplification via a suitable gain resistor to a –10 to 10 V signal which is returned to the data acquisition card for analysis. The other signal is ac filtered, amplified and returned to the data acquisition card. The PC and all the electronics are powered from the mains through an isolation transformer and the common ground for all the equipment is the source wall.

Software

A LabVIEW™ computer program was developed to run the data acquisition and the data analysis. The program generates the output waveform to the Kepco power supply. The output waveform consists of a dc bias with the modulated ac signal (e_m) superimposed. The frequency settings used throughout were ω=10 kHz and $p= \omega/(2\pi)$, the dc bias was swept from –20 to 20 V and E was varied from .01 to 1 V.

The program reads the probe current signals and filters the ac channel using a software fast Fourier transform bandpass filter and records the rms value of the required frequency component as a function of applied dc probe voltage. The dc value of the probe current is also recorded in order to generate a traditional Langmuir probe trace for comparison.

Analysis

The data analysis is performed in a separate program module. Firstly the plasma potential is found from the zero of the 2nd derivative. The EEDF is then determined and the integrals evaluated to obtain the electron density and the effective electron temperature. The EEDF data is fitted to the Druyvesteyn formula, $N(\in) = aV^{0.5}\exp(b\in^{c})$, using a non-linear least squares fitting method.

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

i. The Orbital Motion Limited (OML) theory of ion collection [6,9].

ii. The Allen-Boyd-Reynolds (ABR) radial motion theory of ion collection [5].

iii. Bernstein-Rabinowitz-Laframboise (BRL) theory of ion collection [7].

iv. Classical Langmuir-Mott Smith (LMS) theory for electron collection [9].

In all cases the pertinent data is extracted from the trace and is fitted to the theory using the Levenberg-Marquart non-linear fitting method. Classical Langmuir theory determines an electron temperature based on the assumption that the electrons have a Maxwellian distribution. OML, BRL and ABR theories can be used to infer electron temperature but these methods are is very unreliable as only a small portion of the electrons in the high energy range are considered. The energy distribution in this range is very likely to differ from the rest of the distribution unless there is a strong influence of electron-electron interactions. Hence it is preferable to use Langmuir theory to infer T_e and then use this value to fit the OML, BRL and ABR theories.

Results

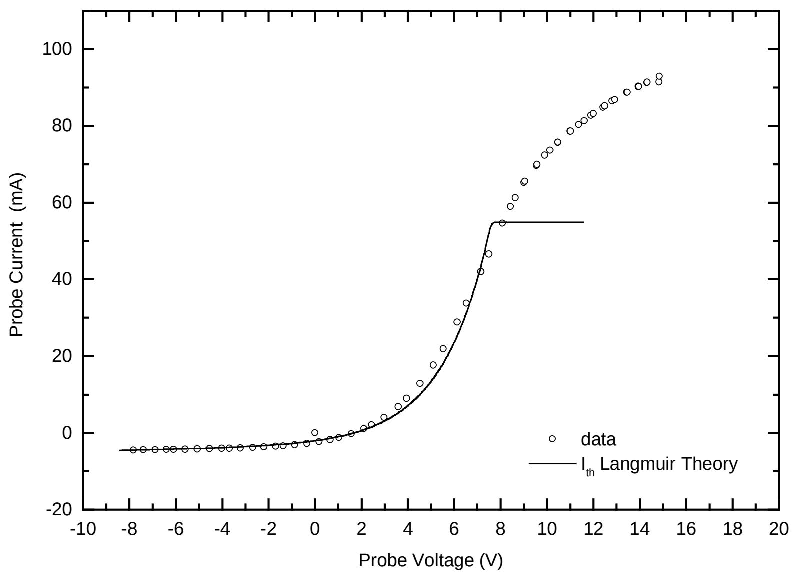


Figure 3 Langmuir probe trace raw data and electron current best fit

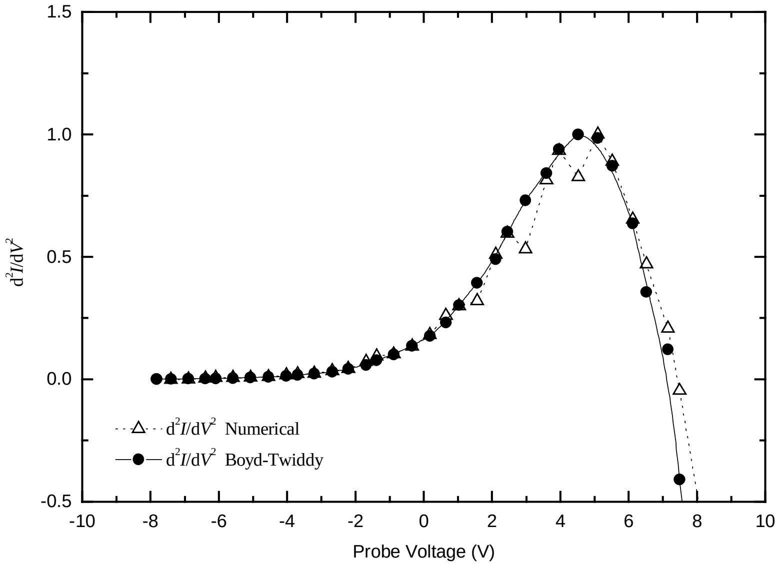


Figure 4 2nd derivative of the IV curve showing numerical and BT method. Measurement taken at the centre of the discharge with arc power is 47 kW and the gas pressure 0.3 Pa.

Figures 3 to 6 show the show the data obtained for a typical shot. In this case the probe was positioned near the centre of the discharge, the arc power was 47 kW and the gas pressure was 0.3 Pa. The results are summarised in table 1. Figure 3 shows the Langmuir probe IV curve raw data (open circles); this data is fitted to the classical Langmuir theory (solid line) applied to the electron retardation region when the probe potential is less than the plasma potential. The theory assumes a Maxwellian electron distribution but it is clear from the figure that the theory does not fit the data very well between 2 and 6 volts. The 2nd derivative of the IV curve from figure 3 is presented in figure 4. The figure also shows the 2nd derivative as obtained by both a standard numerical method (···Δ···) and the Boyd-Twiddy method (—●—). Obtaining the result by a numerical method requires smoothing of the data between successive differentiation operations and the outcome is subject to the choice of smoothing method employed [10]. The Boyd-Twiddy method on the other hand does not require any subjective analysis and it results in a smoother curve than the former method.

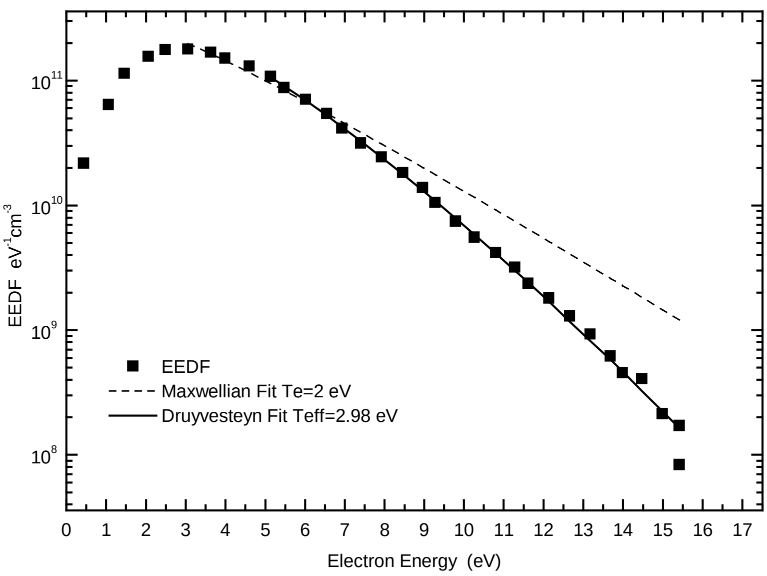


Figure 5. Plot of EEDF with fitted Maxwellian and Druyvesteyn distributions. Measurement taken at the centre of the discharge with arc power is 47 kW and the gas pressure 0.3 Pa.

The plasma potential is found from the zero of the 2nd derivative to be 7.58 Volts and the floating potential is found from the zero of the Langmuir probe trace to be 1.56 Volts. The data from the 2nd derivative (Boyd-Twiddy method) is used together with the measured plasma potential to evaluate the EEDF. This EEDF is shown in figure 5 where it fitted to the Druyvesteyn formula, $N(\in) = a \in^{0.5} \exp(b \in^{c})$, for two values of parameter *c i.e c*=1 for a Maxwellian distribution and *c*=2 for a Druyvesteyn distribution of electrons. It is clear that a Maxwellian is not the best fit for the data. Integrating the data from figure 5 according to equations 3 and 4 gives n_e=1.6×10^{12} cm^{-3} and T_{eff}=2.98 eV. Analysis of the electron retardation region of the *I-V* curve using classical Langmuir theory yields n_e=9×10^{11} cm^{-3} and T_e=2.05 eV. An increase from 2 eV to 3 eV in the electron temperature results in a change from 1×10^{-17} cm^2 to 1.1×10^{-16} cm^2 in the value of the cross section for electron impact detachment of H^- [11].

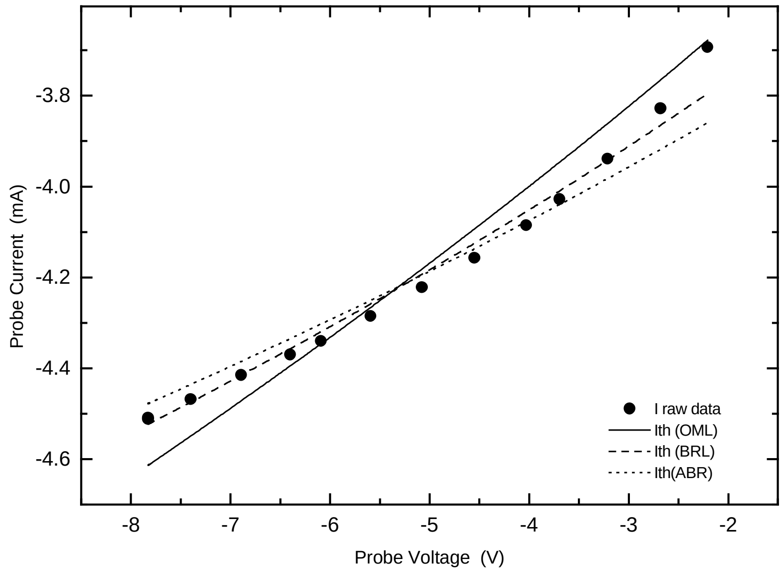
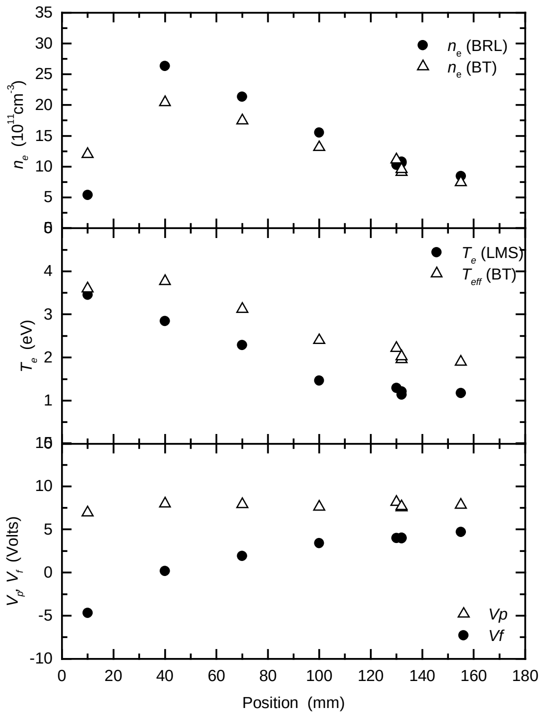


Figure 6 The ion current fitted to ABR OML and BRL theories of ion collection.

Figure 6 shows the ionic current fitted to the different theories of ion collection. It was found that the BRL theory fits the data better than the others. This is not surprising since the BRL theory is the most complete (and most difficult to implement), taking account of sheath expansion, collisions and finite ion temperature. The BRL theory is fitted to the data following a procedure described in [12].

V_p V	V_f V	T_e (LMS) eV	T_{eff} (BT) eV	n_e (BT) cm^{-3}	n_e (LMS) cm^{-3}	n_e (OML) cm^{-3}	n_e (ABR) cm^{-3}	n_e (BRL) 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 shown in figure 3



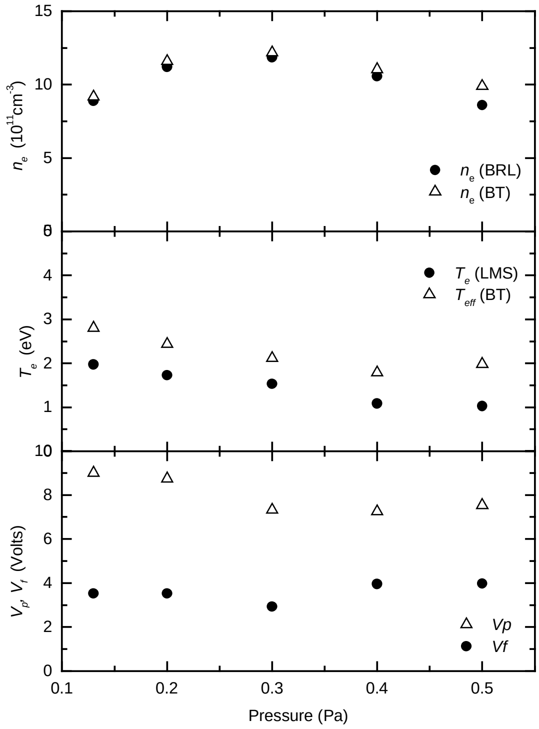
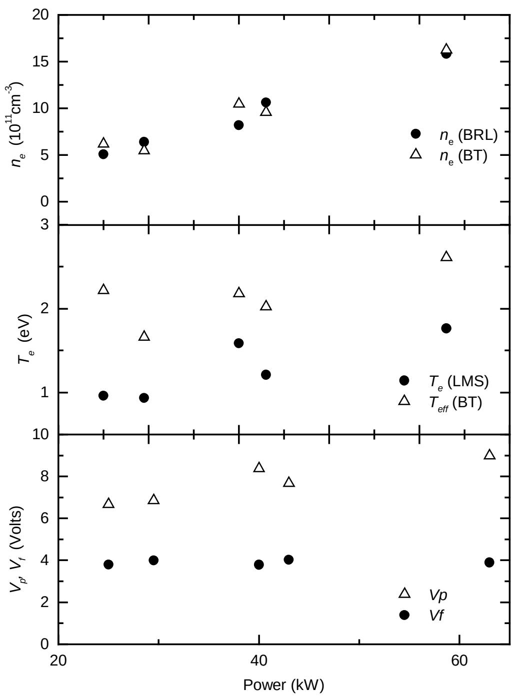


Figure 7 Plasma parameters as a function of position from the edge to the centre of the source.

Figure 8 Plasma parameters as a function of Pressure



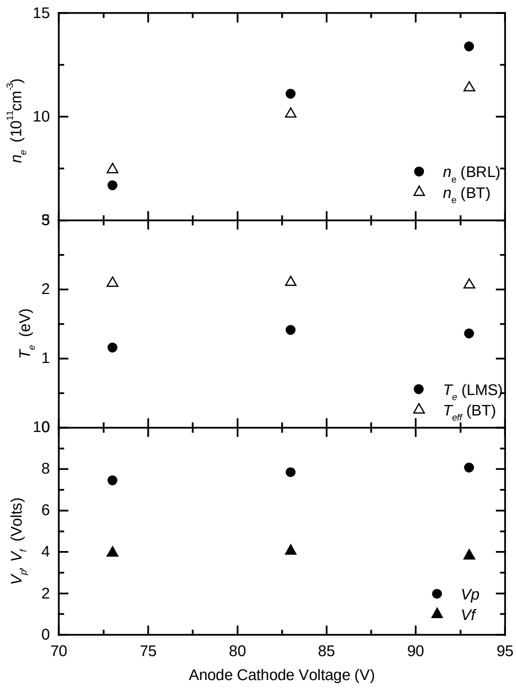


Figure 9 Plasma parameters as a function of Power

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

The plasma parameters were measured as a function of arc power, source pressure, anode-cathode voltage and as a function of probe position. A summary of the results are presented in figures 7 to 10. In each figure the plasma potential and the floating potential are presented together on the bottom graph, T_e and T_{eff} are presented on the middle graph and the plasma density is presented on the top graph.

Figure 7 shows the plasma parameters as a function of position from the edge to the centre of the source. For the scan the arc power was kept at a constant 47 kW and the source pressure was 0.3 Pa. It is found that the plasma potential is almost constant across the source and that the electron temperature decreases towards the centre of the source and that T_{eff} is consistently about 1eV greater than T_e. The plasma density decreases towards the centre of the source.

Figure 8 shows the results of a pressure scan. The power was 47 kW and the results presented are for the central position. The density is maximum at 0.3 Pa and the electron temperature decreases with increasing pressure.

The results of the power scan are shown in figure 9 as expected the temperature and density increase from 5×10^{11} to 1.5×10^{12} cm^{-3} over the power range 25 to 65 kW.

Figure 10 shows the plasma parameters for three values of anode-cathode voltage from 73 V to 93 V. The variation seems to have little effect on T_e but the density increases from 7×10^{11} to 1.4×10^{12} cm^{-3}.

Conclusion

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.

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