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# COMPUTERIZED ANALYSIS OF HYDROGEN PLASMA IN A COMPACT H⁻ CUSP SOURCE



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## ABSTRACT

A cylindrical Langmuir probe with diam of 0.5 mm, length of 5 mm and the Laframboise theory are used to give an analysis of the plasma parameters in a $H^-$ cusp source including temperatures and densities of slow, fast electrons and positive ions in a median density plasma. The iteration technique overcomes the problems of conventional Langmuir probe analysis. A VAX based program is used to control the motion and analyze data from the probe. In this paper, we briefly describe the program and present initial results obtained from a compact $H^-$ volume multicusp source.

## INTRODUCTION

To date, the Langmuir probe is still one of best techniques to analyze and understand the process in a hydrogen plasma. In order to take a spatial measurement over the entire region of the plasma a computerized technique is required, which gives a fast measurement and analysis of the plasma parameters. TRIUMF has developed two $H^-$ dc cusp sources which have shown some advantages over the other sources. The sources are divided into two regions (1) driver region, (2) extraction region separated by a magnetic filter, which allows cold electrons ($\sim$ 1 eV) to penetrate with positive ions into the extraction region from the driver region, but stops fast $e^-$ from doing so. Consequently, $H^-$ ions are formed in the extraction region and extracted. In this paper the development of a VAX computer controlled Langmuir probe as a plasma diagnostic is described. The technique provides a rapid measurement by a modified program initially developed for emittance measurements and an iterative analysis using the Laframboise theory[1], which shows a good agreement of positive ion current with experiment to a highly negative biased probe and also allows the measurement of fast electrons.

## EXPERIMENTAL SETUP

A compact cusp source[2] is used in the experiment. A cylindrical Langmuir probe with a tungsten wire (0.5 mm in diameter and 5 mm in length) is driven by a stepping motor along the entire axis of the source and measures an I–V curve at each axial position. The block diagram of the data acquisition system is shown in Fig. 1. A stepping motor is controlled by a VAX to bring the probe to the requested positions in the source through CAMAC. A step voltage is applied at each position to the probe from a -V to a +V. At each step of the voltage the current is collected by the biased probe to form the data of I–V curve stored in the VAX. In order to have a good resolution there is a natural scaling parameter $\chi = e(V - V_p)/kT_e$. The accuracy of fitted curve depends on the number of the points per $\chi$ rather than per volt. In the extraction region $kTe \leq 1$ eV 700 points are acquired for the I–V curve.

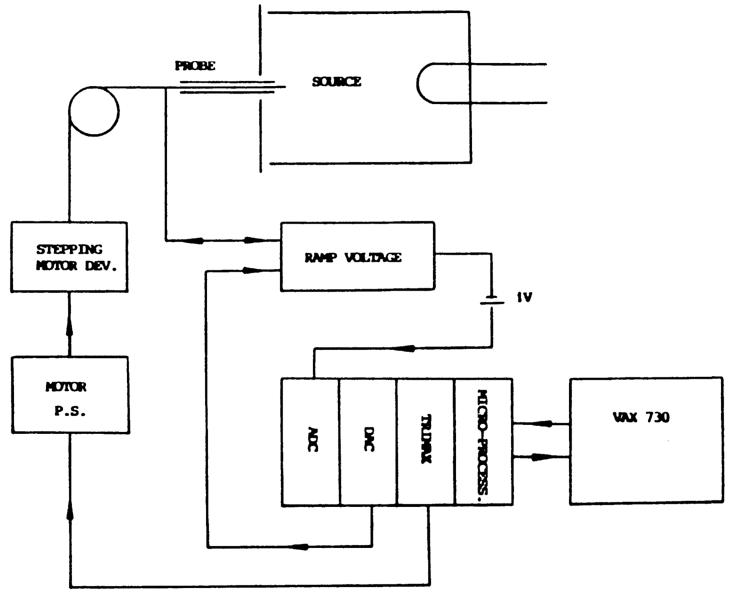


Fig. 1. Scematic of probe system.

## PROBE THEORY

An ideal I–V curve is shown in Fig. 2. After a cylindrical Langmuir probe has been inserted into the plasma, a plasma sheath is formed around the probe. The thickness of the sheath depends on the voltage applied to the probe with respect to the anode of the plasma chamber (see Fig. 3). Here the following symbols are used: $V$, the potential difference between the probe surface and the anode which is composed of two parts; namely the potential drop between the anode and the sheath boundary, $V_p$, and the potential difference of the probe surface with respect to the sheath edge $V_{sh}$. If the probe potential $V_{sh}$ is sufficiently negative i.e. $-eV_{sh} \gg kT_e$, which is achieved by making $V$ more negative with respect to $V_f$, the floating potential, almost no low $e^-$ will reach the probe while all positive ions passing the sheath edge in the direction of the

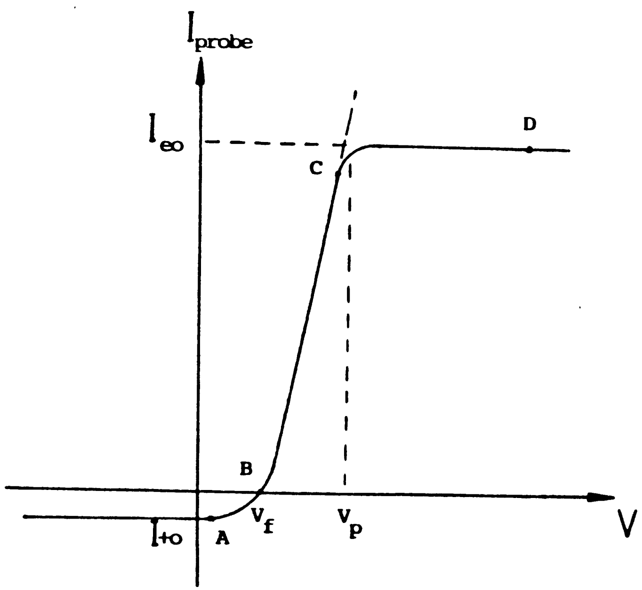


Fig. 2. I–V curve of an idealized probe.

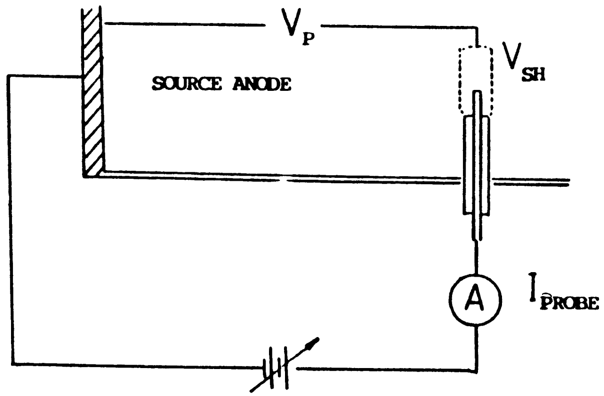


Fig. 3. Probe circuit.

probe are absorbed. Some higher energy $e^-$ still can penetrate the sheath to the probe. As $V$ is made more and more negative the high $e^-$ become less and eventually no $e^-$ are observed. The probe current then is equal to the ion saturation current $I_{+0}$:

$$I_{+0} = \frac{1}{4} e n_+ A \left(\frac{8kT_e}{\pi m_+}\right)^{\frac{1}{2}} \tag{1}$$



where $n_+$ is the ion density in the undisturbed plasma and $A$ is the probe surface area. Raising $V$ in the other direction, higher than $V_f$, more and more $e^-$ are able to overcome the retarding potential drop; initially, the faster $e^-$ of the velocity distribution and at still higher positive voltage of $V_{sh}$ also the slower $e^-$. Simultaneously the thickness of the ion sheath decreases. The density distribution of Maxwellian electrons in the positive sheath is governed by Boltzman's law ($V < V_{sh}$):

$$n_e = n_0 \exp\left(\frac{e(V - V_{sh})}{kT_e}\right) \tag{2}$$

As $V$ approaches $V_p$, at point C in Fig. 2, the space charge sheath in front of the probe vanishes. This point of the characteristic corresponds to the condition:

$$V_{sh} = 0; \qquad V = V_p; \qquad I_{\text{probe}} = I_{+0} + I_{e0}.$$

Since the mean velocities of the ions are much smaller than those of the electrons, $I_{\text{probe}}$ may be approximated by ($V = V_p$):

$$I_{\text{probe}} \cong -\frac{1}{4} e n_e A \left(\frac{8kT_e}{\pi m_e}\right)^{\frac{1}{2}} \tag{3}$$

which is the $e^-$ saturation current. In practice, in the medium density plasma ($10^{10}$ to $10^{12}\text{cm}^{-3}$), the I–V characteristic does not saturate moving to the right from point C. The nonsaturation of the current to the probe is explained by considering in the extraction region the current collected to a probe of increasing effective area (even larger in the driver region). It is due to additional ion production in the presheath region. Customarily it is overcome by linearly extrapolating the ion current measured at highly negative voltage, to give the expected saturation current at the plasma potential. Therefore, It was found that the value of $n_+$ can vary by almost an order of magnitude in the driver region and by a factor of 2 in the extraction region. This indicates that the expansion of ion current is nonlinear, and the extrapolation technique does not provide a accurate result. Laframboise theory provides a numerical solution to the equations which govern ion collection in a stationary collisionless plasma, and a set of ion expansion curves have been deduced from this theory. These curves are a function of the ratio of the radius of the probe, $R_p$, to the Debye length, $\lambda$, which is given by

$$\lambda = \left(\frac{\epsilon_0 kT_e}{e^2 n_e}\right)^{\frac{1}{2}} \tag{4}$$

where $\epsilon_0$ is the permittivity of free space. Laframboise used the plasma potential as a reference. A natural scaling parameter $\chi = e(V - V_p)/kT_e$ is introduced (Fig. 4). We assume in the calculation that the dominant ion species is $H_3^+$;

the other ion densities are neglected. From the theory the expansion of the ion current to the probe can be written as a function of applied voltage $\chi$:

$$\frac{I_+(\chi)}{I_{0+}} = f\left(\frac{R_p}{\lambda}, \chi\right) \qquad \chi < 0 \tag{5}$$

where $I_+(\chi)$ is the ion current to the probe as a function of $\chi$ or probe voltage. $I_{0+}$ is the ion saturation current at plasma potential. $f(R_p/\lambda, \chi)$ is the ion current expansion factor as calculated in the theory in the zero ion temperature limit (see Fig. 4). $R_p$ is the radius of probe.

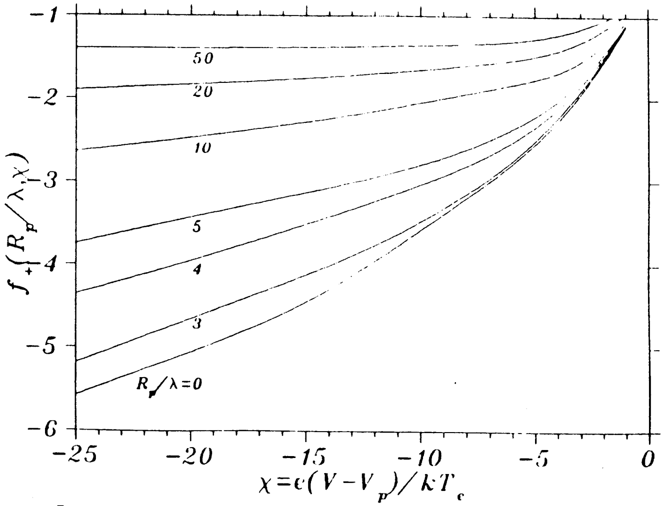


Fig. 4. Ion current expansion factors as a function of natural scaling parameters, $\chi$ for various values of $R_p/\lambda$.

## PROGRAM DESCRIPTION

In order to use Laframboise theory to analyze the I–V curve, one has two difficulties. First, the theory uses the plasma potential $V_p$ as a reference value, which is not yet known. Secondly,one needs to select a particular theoretical curve from Fig. 4, which depends on the ratio of the probe radius to the electron Debye length, $R_p/\lambda$. This ratio, in turn, depends on $kT_e$ and $n_e$, which have to be determined. A iteration technique is used here to solve the problems and give accurate results of the plasma parameters.

### Initial $V_p$, $kT_e$, and $n_e$

A derivative of the equation (2), $dI(V)/dV$, gives a maximum value at the plasma potential, $V_p$, and

$$\frac{I(V)}{dI(V)/dV} = \frac{kT_e}{e} \tag{6}$$



That is, in the exponential region, the ratio of current to the first derivative is equal to the electron temperature, $kT_e$ in units of eV. When the first derivative passes through the maximum, the current and voltage at maximum, $I_{\text{maxderiv}}$, $V_{\text{maxderiv}}$ and the value of derivative itself, $I'_{\text{max}}$ are stored in the computer. We assume when the first derivative reaches 1/10 of $I'_{\text{max}}$, the probe current is a reasonable estimate of saturation $e^-$ current, $I_{\text{sat}}$.

To a first approximation we then have

$$V_p = V_{\text{maxderiv}},$$
$$kT_e = \frac{I_{\text{maxderiv}}}{I'_{\text{max}}},$$
$$I_{0e} = I_{\text{sat}}$$

where $I_{0e}$ is the maximum electron current at plasma potential.

$V_p$ and $\chi$ can be expressed as a function of voltage. Figure 5 shows the I–V curve and its first derivative. Customarily, $V_p$ is determined by the voltage at which the exponential region of I–V curve intersects the saturation current. Here it can be approximated by

$$V_p = V_{\text{max}} + kT_e/e \ln\left(\frac{I_{\text{sat}}}{I_{\text{maxderiv}}}\right) \tag{7}$$

Substituting $kT_e$ and $I_{0e}$ into equations (3) and (4) gives the initial values for $n_e$ and $\lambda$.

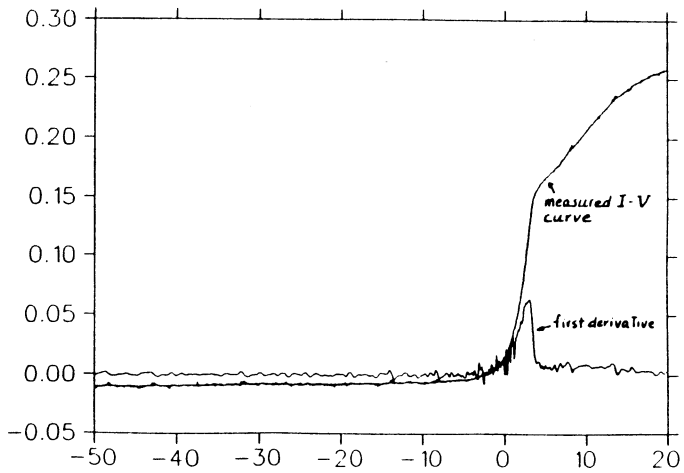


Fig. 5. Experimental curve.

Calculation of $n_+$

The first approximation of $kT_e$, $V_p$, and $n_e$ are used to calculate the parameter $R_p/\lambda$ and the function $\chi$, and to select a curve in Fig. 4, which is fitted and stored in the computer. From Eqs. (1) and (5) we get

$$n_+ = \frac{4I_+(\chi)}{eA(8kT_e/\pi m_+)^{1/2} f(R_p/\lambda, \chi)} \qquad (8)$$

where, again, $I_+(\chi)$ is the current to the probe at a negative voltage wrt the plasma potential.

The measurement of $I_+(\chi)$ is complicated due to the presence of both the tail of Maxwellian distribution of the thermal $e^-$ in the form of $I_{0e}\exp(\chi)$ and fast $e^-$. This is overcome by measuring $I_+(\chi)$ at a sufficiently negative voltage to remove contributions from all electrons.

Calculation of $n_{fe}, kT_{fe}$

For $\chi < -10$, the bulk thermal $e^-$ contribution is effectively zero. Then, the current to the probe due to the collection of fast electrons $I_{fe}(\chi)$ is calculated as follows:

$$I(\chi) = I_+(\chi) + I_{fe}(\chi)$$

where $I(\chi)$ is the measured current to the probe and $I_+(\chi)$ is the ion contribution. Thus we have:

$$I_{fe}(\chi) = I(\chi) - \frac{1}{4} e n_+ A \left(\frac{8kT_e}{\pi m_e}\right)^{\frac{1}{2}} f\left(\frac{R_p}{\lambda}, \chi\right) \qquad \chi < 10$$

$I_{fe}(\chi)$ is fitted by an exponential regression to:

$$I_{fe} = I_{0fe} \exp\left(\chi \frac{kT_e}{kT_{fe}}\right)$$

where $I_{0fe}$ is the fast electron current to the probe at plasma potential, $V_p$, and $kT_{fe}$ is the fast electron temperature.

Figure 6 shows an exponential fit to the experimental curve after positive ion contribution subtracted.

Iteration

Now, we have the initial values of $kT_e, n_e, V_p, n_+, kT_{fe}$, and $n_{fe}$. The contribution to the probe current due to fast electrons and the ion current are subtracted from the probe current in the region $-2 < \chi < 0$ (see Sec.5 discussion). The remaining current is due to the low energy electrons only:

$$I_e(\chi) = I(\chi) - I_+(\chi) - I_{fe}(\chi) \qquad -2 < \chi < 0$$

$\ln[I_e(\chi)]$ is then fitted by a linear regression to $V$. The inverse of the slope gives



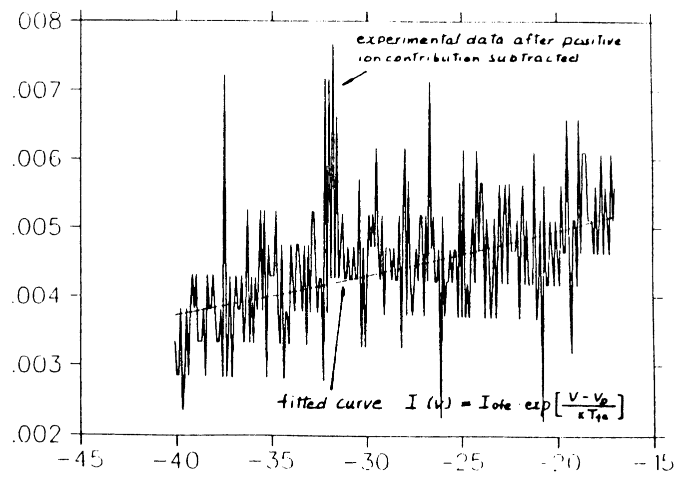


Fig. 6. Experimental curve fit for fast electron.

new values of $kT_e$ and $n_e$ with the ion and fast electron current removed. The plasma potential is corrected in a similar manner (Eq. (7)) by:

$$V_p(new) = V_p(old) + kT_e/e \ln\left(\frac{I_{0e}(new)}{I_{0e}(old)}\right)$$

These new values define a new $\chi$ as a function of the probe voltage and a new value of $R_p/\lambda$. Now the program goes back and repeats the calculations of all the plasma parameters until a self consistent solution is reached. We continue the calculation until $V_p$ converges to within 5% of the previous estimate. In calculation of $V_p$, $I_{0e}$ is replaced by $I_{0e} + I_{0fe}$.

Figure 7 shows an exponential fit to the experimental curve after contributions of positive ion and fast electrons subtracted.

Calculation of $V_f$

The floating potential ,$V_f$, is calculated as the I–V curve passes through zero.

The results of plasma parameters of TRIUMF small dc cusp source calculated using the program are shown in Fig. 8.

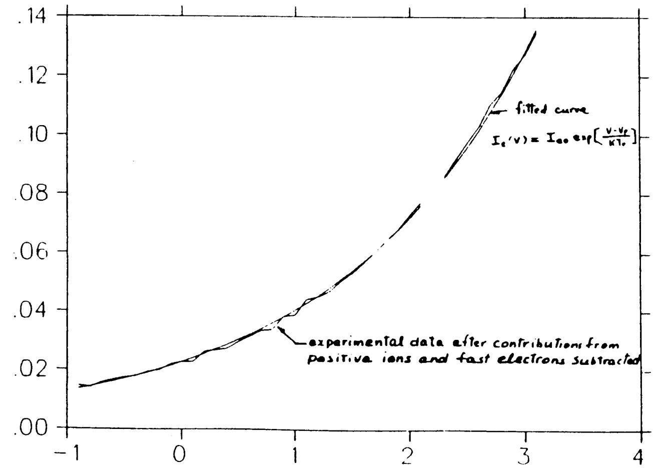


Fig. 7. Experimental curve fit for low electron.

## DISCUSSION

It is believed that a probe biased near or higher than the plasma potential may seriously disturb the local plasma and lead to an error in the measurement of the saturation electron current. There are three possible sources of error. First, the probe collects charged particles from the plasma. This problem is partially overcome by making the area of the probe as small as possible. The probe area we used was 0.08 $cm^2$, which takes a current of the order of 4 mA which is negligible comparing to the arc current. Secondly, there is a possible error resulting from an effect observed by Kunkel[3] due to a depletion in the number of electrons with energy less than or equal to $kT_e/2$. This results in an electron saturation current lower by a factor of two or more. It is assumed that the depletion of low electron occurs. In order to compensate for this effect, the plasma potential is calculated by extrapolation of the points lying lower than the plasma potential which, in tern, was calculated during the previous iteration cycle, and the points above that are not used. Thirdly, there is a depletion due to the magnetic field, which in the small cusp source is 5G in the driver region and up to 150G in the filter region. In order to use the probe in a magnetic field, it is important to satisfy the relationship $R_p/R_{\text{larmor}} \ll 1$, where $R_p$ is the radius of the probe and $R_{\text{larmor}}$, the Larmor radius. Customarily, $R_p/R_{\text{larmor}} = 0.25$ is the criterion, below which the perturbation is small. With this condition, in our case, the magnetic field has to satisfy:

$$B(G) < 20\sqrt{kT_e(eV)}$$



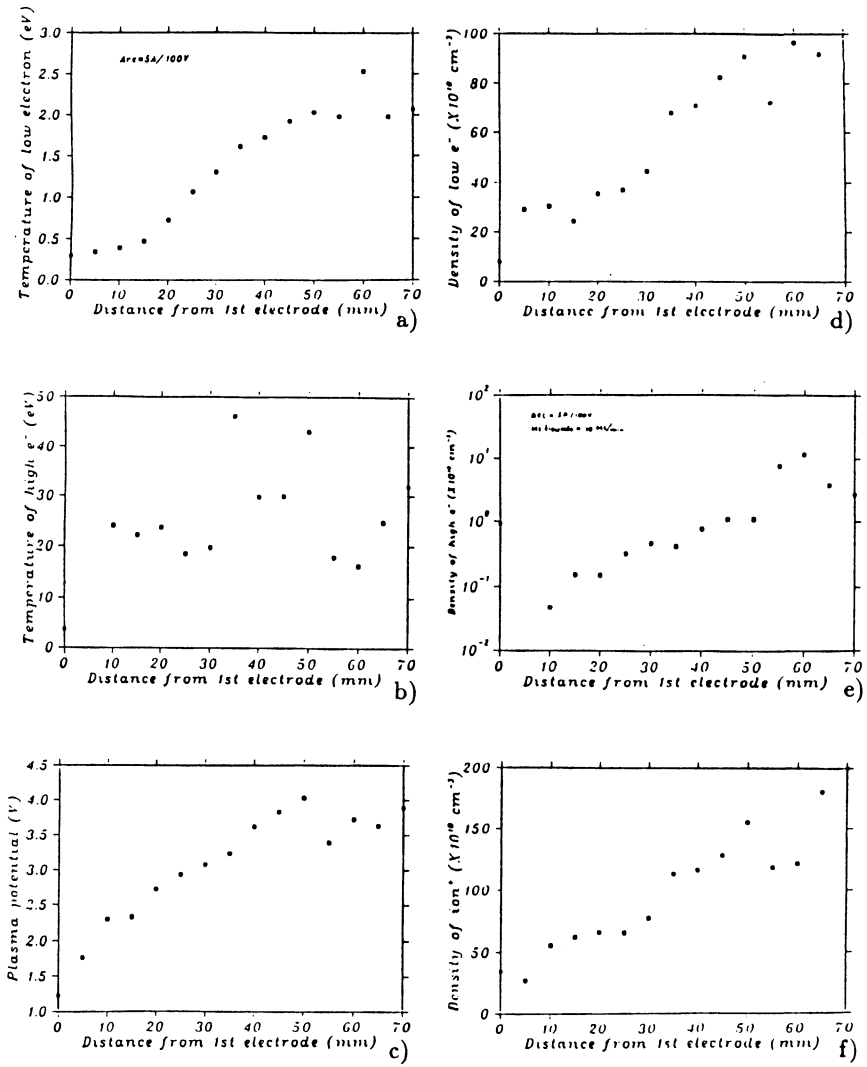


Fig. 8. Plasma parameters at positions from the extractor. a) Low energy electron temperature, $KT_e$; b) high energy electron temperature, $kT_{fe}$; c) plasma potential, $v_p$; d) low energy electron density, $n_e$; e) high energy electron density, $n_{fe}$; f) positive ion density, $n_+$.

It is a problem in the extraction region of the $H^-$ cusp sources where the electron temperature is low ($< 1eV$) and the B field is relatively high. In order to meet the criterion a very small diameter probe has to be used. In our case, the probe dimensions lead to a significant perturbation in the extraction region.

In the calculation of $kT_{fe}$ and $n_{fe}$, a Maxwellian distribution was used. In order to validate this, the second derivative of the fast electron current could be taken by the computer. This has not yet been done, however, it has been established that a bi-Maxwellian energy distribution is a good approximation by the method of Druyvesteyn[4], for an isotropic distribution. In a low pressure, the primary electrons rebounding many times from the magnetic field ensure an isotropic distribution.

## ACKNOWLEDGMENTS

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## REFERENCES

1. J.G. Laframboise, University of Toronto, Institute for Aerospace Studies Report No. 100 (1966):and in Rerefield Gas Dynamics, edited by J.H.de Leeuw (Academic, New York, 1965), Vol. II, p.22.
2. D.H. Yuan, K. Jayamanna and P.W. Schmor "A Small Intense dc $H^-$ Cusp Source in TRIUMF"; to be published.
3. K.F. Schoenberg and W.B. Kunkel, J. Appl. Phys. **50**, 4685 (1979)
4. M.J. Druyvesteyn, Z. Phys. **64**, 781 (1930).