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LABORATORY PLASMA PROBE STUDIES

Walter J. Heikkila
Plasma laboratory experiments and data reduction continued during this reporting period. This report summarizes some of the data obtained on electrostatic resonances observed in the plasma generated at The University of Texas at Dallas.

Dr. Rainer Kist* and UTD personnel utilized a UTD developed digital Langmuir probe plus RF probes to study resonances generated in a collisionless laboratory CO₂-plasma. Laboratory instrumentation, including the Langmuir probe output, were connected to the PDP 11/45 digital computer which automatically recorded and reduced probe data.

The main body of this report is presented in the following two papers written by Dr. Kist.

Appendix A: Plasma Probe Measurements in a Collisionless Laboratory CO₂-plasma.

Appendix B: Operation of a Digital Langmuir Probe on Line with a PDP 11/45 Digital Computer

*On leave at UTD, sponsored by the European Space Research Organization (ESRO), now European Space Agency (ESA).
Plasma Probe Measurements in a
Collisionless Laboratory CO₂-Plasma

by Rainer Kist

This memo describes diagnostic experiments performed in a collisionless plasma using CO₂ as working gas. In particular simultaneous measurements that have been performed by means of Langmuir- and RF-probes are presented. A resonance occurring above the parallel resonance in the frequency characteristic of a two electrode system is interpreted as being due to the resonant excitation of electroacoustic waves. The memo represents a part of the accomplishments achieved in the course of a laboratory plasma investigation at the University of Texas at Dallas (UTD).

+ On leave at UTD, sponsored by the European Space Research Organization (ESRIN), now European Space Agency (ESA).
Introduction:

Studies with diagnostic probes in laboratory plasmas have several important advantages as compared to space plasma investigations:

1) Systematic variation of the parameters involved with the possibility of measuring over large time intervals and of repeating the measurements.

2) Extensive testing of the performance of space plasma probes in a plasma environment prior to a space mission.

3) Systematic investigation of specific plasma phenomena with the aim of improving existing or developing new diagnostic methods.

4) Extensive investigation of various phenomena such as plasma wave mode generation and propagation, instable plasma states and nonlinear effects.

5) Relatively low cost and short time period needed for realizing a plasma experiment.

The results of such laboratory plasma investigations may provide data for checking on particular theories in plasma physics or have impact upon the understanding in fields like space plasmas (planetary ionospheres, magnetosphere, solar wind etc.) or even (after scaling up the results properly) fusion plasmas.

For the space plasma physicist the laboratory plasma is and will remain a very valuable tool even though in the coming space age the ionosphere itself may be used for particular investigations as a large scale "laboratory" plasma of low density and temperature.
In the piece of work presented here the influence of the electron temperature on the frequency characteristic of the plasma impedance of a two electrode system was investigated. Of particular interest was the resonant excitation of electro-acoustic waves within two RF electrodes for different geometries and plasma conditions.

**Experimental System**

A stainless steel vacuum chamber, 70 cm long and 50 cm in diameter, has been equipped with a plasma source which uses CO$_2$ as working gas. A turbomolecular pump together with a copper shroud which was cooled down to liquid nitrogen temperature provided a background vacuum of about $10^{-6}$ Torr. Fig. 1 shows the source schematically. The general concept was to produce a discharge plasma in a separate volume $V_1$ (bell jar) and let it expand into the volume $V_2$ (chamber) through a diaphragm. During operation typical pressure values were $10^{-2}$ Torr in volume $V_1$ and $10^{-4}$ Torr in volume $V_2$. In order to control the pressure gradient and the plasma source performance the diaphragm was an iris which could be varied by means of a feedthrough mechanism. A heated tungsten cathode provides primary electrons for the discharge as well as neutralizing electrons for the ions moving from the discharge region into the tank. A paddle proved very useful in baffling high energetic electrons coming from the discharge.

A set of different plasma probes were installed in the tank, in particular

a) a conventional Langmuir probe (LP)

b) a retarding potential analyzer (RPA) and

c) electrode systems for RF impedance measurements.
Fig. 2 shows schematically the arrangement of the plasma source and the probes in the vacuum system. The probes were mounted on movable high vacuum feedthroughs in order to change their position and/or orientation within the tank.

The RF-measurements presented in this memo were performed with a cylindrical and a spherical two-electrode system $(E_1, E_2)$, as shown in Fig. 3. The principle of the RF-measurement is also shown. A swept frequency RF generator provides a signal of constant amplitude within the frequency interval of typically 1 to 25 MHz. The RF-reference voltage $U_R$ at $E_1$ as well as the test voltage $U_T$ at $E_2$ are measured and compared as to their complex ratio

$$\frac{U_T}{U_R} = E + jF$$

by means of a network analyzer hp 8407.

The signals provided by the network analyzer are magnitude

$$\alpha = \left| \frac{U_T}{U_R} \right| = \sqrt{E^2 + F^2} \quad \text{in dB}$$

and phase $\psi = \arctan (F/E)$ in degrees. Magnitude and phase together are a measure for the complex plasma impedance $Z = X + jY$ between $E_1$ and $E_2$. In case of the spherical system half spheres were used as $E_1$ and $E_2$. Additional half spheres were operated as guard electrodes in order to reduce the influence of the tank walls.

In Fig. 4 are shown current-voltage characteristics of a spherical (diameter: 10 mm) stainless steel Langmuir probe.
The parameter of this set of curves is the bias voltage $U_1$ of the plasma source heating circuit. It can be seen that the velocity distribution and temperature $T_e$ of the electrons is markedly influenced by $U_1$. In the present case the distribution function is maxwellian in good approximation for $U_1$-values of $-2$ V, $-3$ V and $-4$ V. The corresponding $T_e$-values are 0.55, 0.53 and 0.52 eV, respectively. For each of these Langmuir curves the magnitude $\alpha$ measured as function of frequency was plotted on a X-Y-recorder. Fig. 5 shows the corresponding set of curves, which reveals the following essential features:

a) above the parallel resonance $f_p$, which is in our case (no magnetic field) equal to the plasma frequency $f_{nw}$, occurs an additional resonance $f_z$, and

b) $f_z$ is pronounced most clearly for the case of maxwellian distribution of the electrons with low electron temperature $T_e$ ($U_1 = -2$ V, $-3$ V, $-4$ V).

This resonance $f_z$ can be understood in terms of electroacoustic waves (also called electron pressure or Landau waves) which are launched by an RF-source above the plasma frequency. Excitation of this electrostatic type of plasma wave, which is damped with increasing frequency by collisionless or Landau damping, is predominantly responsible for the real part of the impedance of an electrode system immersed into a plasma. For a single electrode this real part would decrease monotonically with increasing frequency. For a two electrode system $(E_1, E_2)$ as used in our experiment, however, a characteristic electrode distance $d$ can be defined (distance between inner and outer cylinder or between two spheres). In this case the electroacoustic wave can produce a standing wave pattern between $E_1$ and $E_2$. This is expected to occur essentially at eigenfrequencies of the system electrodes-plasma, for which the wavelength $\lambda_{ea}$ (or integer multiples of it) matches the distance $d$.\[\text{ORIGINAL PAGE IS OF POOR QUALITY}\]
To check this interpretation we start with the Bohm/Gross (1959) dispersion relation for these plasma waves

\[ \omega^2 = \omega_N^2 + \left(3 \frac{K T_e}{m_e} \right) k^2 \]  

(1)

Here \( \omega \) is the angular RF-frequency, \( \omega_N \) the angular plasma frequency, \( K \) is Boltzmann's constant, \( m_e \) the electron mass and \( k = 2 \pi / \lambda_{ea} \) the electroacoustic wave number. Equation (1) gives the wavelength \( \lambda_{ea} \) at the resonance frequency \( f_Z = \omega_Z / 2 \pi \) :

\[ \frac{\lambda_{ea}}{m} = 0.7263 \frac{\sqrt{K T_e / eV}}{f_N \sqrt{\frac{f_Z^2}{f_N^2} - 1}} \]  

(2)

Applied to the measurements of Fig. 5 we get the following table 1:

<table>
<thead>
<tr>
<th>( U_1 / V )</th>
<th>( T_e / eV )</th>
<th>( f_Z / f_N )</th>
<th>( \lambda_{ea} / \text{mm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 1</td>
<td>.61</td>
<td>1.40</td>
<td>56</td>
</tr>
<tr>
<td>- 2</td>
<td>.55</td>
<td>1.34</td>
<td>54</td>
</tr>
<tr>
<td>- 3</td>
<td>.53</td>
<td>1.31</td>
<td>56</td>
</tr>
<tr>
<td>- 4</td>
<td>.52</td>
<td>1.30</td>
<td>52</td>
</tr>
<tr>
<td>- 5</td>
<td>.65</td>
<td>1.32</td>
<td>54</td>
</tr>
<tr>
<td>- 6</td>
<td>.85</td>
<td>1.38</td>
<td>54</td>
</tr>
</tbody>
</table>

The distance of the cylindrical electrodes is \( d = 53 \) mm. Due to the cylindrical geometry (equation (1) is strictly valid for plane waves), to the ion sheath, and possible inhomogeneous plasma distribution within the electrodes one cannot expect
an absolute agreement between $\lambda_{ea}$ and $d$. But we have as an essential result, that the ratio $\lambda_{ea}/d$ is constant within a few percent for all combinations ($f_N$, $f_Z$, $T_e$) that occur in the set of curves of Fig. 5.

Theoretical work done by Whale (1963), Balmain (1965) and Lin/Lei (1970) shows that excitation of electroacoustic waves is reduced by the presence of an ion sheath. On the other hand, collapsing the ion sheath by changing the electrode bias potential to the plasma potential leads to electron absorption so that damping of the electroacoustic wave is to be expected, too. Thus varying the electrode DC-potential $U_{DC}$ from negative (ion sheath extended) to positive (ion sheath "collapsed"), a value for $U_{DC}$ should occur for which the resonance at $f_Z$ is best pronounced.

The curves of Fig. 6, where the potential $U_{DC}$ of the test electrode $E_2$ was varied, exhibit exactly this behaviour and thus seem to confirm the interpretation for the $f_Z$-resonance suggested above.

Measurements with the spherical electrode system also show the resonance $f_Z = f_{Z1}$ as can be seen from Fig. 7. In this case the distance $d$ of the two spheres was varied. In case of the large distance $d = 92.8$ mm a second resonance $f_{Z2}$ above $f_{Z1}$ occurs. These measurements were analyzed on grounds of a theory by Chasseriaux et al. (1972), in which the potential of an oscillating point charge in a warm isotropic plasma is calculated using kinetic plasma theory. The results predict resonances of the potential and hence of the plasma impedance of a spherical system essentially at those frequencies, at which the wavelength $\lambda_{ea}$ (or integer multiples) equals the distance $d$ between the spheres. As to our experiment we thus have to check, if the measured values for $d$, $f_{Z1}$ (and $f_{Z2}$) and $f_N$ lead to the same electron temperature. The result of this analysis is presented in table 2.
Again the essential result is that all cases lead in fact within a few percent to the same mean temperature $T_e = 46$ eV. In case of $d = 65.8$ mm the error in $T_e$ is relatively large due to the larger error in reading the resonance frequency $f_Z$. The mean value for $T_e$ is indicated by the straight line drawn into the corresponding Langmuir characteristic of Fig. 8. The additional resonance at $f_{Z2}$ leads, applying the theory of Chasseraux et al., to the value $T_e = .51$ eV. This value still seems to be reasonable in view of several error sources like reading error for $f_{Z2}$, deviation of the velocity distribution of the electrons from maxwellian, presence of an ion sheath around the electrodes etc.

The experiments presented here show that a system of two RF-electrodes lead to additional resonances of the impedance characteristic above the plasma frequency which can be understood in terms of resonant excitation of electroacoustic waves.

Systematic and more detailed investigations of the plasma impedance of two electrode systems will be performed in the big plasma chamber at IPW/Freiburg. The importance of the additional resonance $f_Z$ relies on two aspects:

1) knowing the distance $d$ and the plasma frequency $f_{NN}$, $f_Z$ allows in principle to deduce the electron temperature $T_e$.

+ IPW = Institut für Physikalische Weltraumforschung.
2) This method would allow to determine $T_e$ with high temporal resolution ($10^{-1}$ to about $10^{-2}$ sec) which would be of particular value for diagnostic measurements in space plasmas as well as non stationary laboratory plasmas.

Acknowledgement:

The author wishes to thank Prof. W. Heikkila and Dr. D. Winningham for valuable discussions and B. Milam for his engineering assistance.
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PLASMA SOURCE

ORIGINAL PAGE IS OF POOR QUALITY

FIG 1
SPHERICAL RF-PROBE
DIAMETER OF BOTH SPHERES: 17.8 mm

CYLINDRICAL RF-PROBE

FIG 3
SPHERICAL LANGMUIR PROBE
STAINLESS STEEL
DIAMETER 10mm
VARIATION OF $U_1$

FIG 4
Cylindrical RF-probe variation of $U_1$
SPHERICAL RF-PROBE
VARIATION OF PROBE DISTANCE d

FIG 7
SPHERICAL LANGMUIR PROBE
STAINLESS STEEL
DIAMETER 10mm

FIG 8
OPERATION OF A DIGITAL LANGMUIR PROBE
ON LINE WITH A PDP 11/45 DIGITAL COMPUTER

by

RAINER KIST*

This memo describes the concept and the performance of the Digital Langmuir Probe (DLP) experiment, the necessary interface electronics to the computer and the associated software. The system was set up to provide a flexible diagnostic tool for the laboratory plasma facility at the University of Texas at Dallas (UTD). The memo summarises a part of the accomplishments achieved in the course of a project which deals with production and diagnostics of collisionless laboratory plasmas at UTD.

UTD, September 1974

*On leave at UTD, sponsored by the European Space Research Organization (ESRO), now European Space Agency (ESA).
I. INTRODUCTION

Several diagnostic probes such as RF-probe, Retarding Potential Analyzer (RPA) and Langmuir Probes (LP) have been installed in the Laboratory plasma chamber at UTD. Langmuir Probes of different materials (Stainless Steel, Polymorphic carbon) and geometry (spherical, cylindrical) have been used. Fig. 1 shows the arrangement of the probes within the chamber. The detailed description and performance of the plasma source and the probes are the object of a separate memo.

A conventional Langmuir probe electronics makes use of an electrometer amplifier with either a nonlinear (diode) feedback resistor or a linear feedback resistor plus subsequent logarithmic amplifier. This allows to display the logarithm of the probe current over 3 to 4 orders of magnitude (current-voltage characteristic). This compressed form of current display, however, does not allow for a sufficient resolution of small current changes as they occur in time and/or space due to density fluctuations associated with electrostatic waves on instabilities present in a plasma.

In order to measure small electron density fluctuations in the F-region of the Equatorial Ionosphere a digital Langmuir Probe (DLP) was developed at UTD by D. Winningham and J. B. Smith for use in the EQUION rocket project. The unique feature of this experiment is to provide an absolute current resolution of \( \approx 10^{-9} \) Amps and a maximum relative resolution of \( \approx 10^{-4} \).

Since the investigation of electrostatic wave modes and instabilities is of special interest for laboratory plasma physics, this DLP was installed for use in the plasma chamber at UTD. In particular the digital output of the instrument allowed for a straightforward connection
to the computer (PDP 11/45). Therefore an interface electronics and a set
of computer programs were set up to transfer the data to the computer and
from there on to magnetic tape and process them for display on a Calcomp
plotter.

A general diagram of the system DLP-Computer is shown in Fig. 2.
The mean parts of the system are described below in more detail.

II. Properties of the DLP - Electronics*

A triangular bias waveform is applied at G (see Fig. 3) through the
electrometer amplifier (1) to the Probe P. The laboratory version of
the DLP allows for using the waveform of either the internal or an external
bias generator. The range for the bias voltage is from -1 to +3 volts.
The period $T$ of the internal bias generator is controlled by the bit
rate fed into the experiment and can be varied between $0.5 \, S \leq T \leq 200 \, S$.
The relationship between $T$ and the bit rate $f_b$ is

$$\frac{T}{S} = \frac{23040}{f_b \text{Hz}}$$

The electrometer amplifier is a 3420L BURR-BROWN with bias current
of about 1 pA and frequency response better than 2 kHz.

The bias waveform at G also appears at A, B, and C. Therefore the
bias is also introduced at J so that Amplifier 2 can see the bias as a
common mode signal, and can reject it, making D independent of the bias
and responsive only to the signal produced by the input current at A.
One of the important system tests consists of holding the input current

*This chapter is essentially the DLP electronics description that already
had been prepared by D. Winningham and J. B. Smith for the EQUION-Project.
constant and letting the bias voltage cycle while observing the output code. If the system is properly adjusted, the output code will not change by more than 1 or 2 LSB's.

The principle of operation is obvious; only a few system constants will be specified here. The A/D converter is a 0 to -10 v full scale, 8 bit unit. Of the total range of 256 increments (called minor increments) only 200 are used, leaving an unused portion at the lower and upper edges of the 10 volt range. The limits of the 200 increment range are determined by voltage comparators. Actually the comparators defined a range of 200 increments plus a hysteresis band of a few increments in order to avoid an oscillatory condition when sitting at band edge. This means that certain values of current can be represented by two different code group differing by 200 minor increments and by 1 major increment. However, when the two code groups are decoded according to a fixed algorithm, exactly the same current results.

When a voltage comparator switches it changes the D/A converter code by one increment (called a major increment). The resulting output analog increment is fed into the system at J which resets the output D by 200 minor voltage increments.

The D/A is an 8 bit unit in which the 256 increments correspond to an output voltage from -10v to +10v. This range establishes the maximum measuring limits of the system, and R₁ is chosen so that the desired maximum current will cause a ± 10v change at B. However the bias voltage must be added to this which results in a range of -11 v to +13 v at B. With a ± 15 volt supply, the +13 v limit exceeds the linear range of operation of amplifiers 1 and 2. Therefore R₁ is chosen to be 786 KΩ.
which results in a maximum voltage at B of \(7.86\ v + 3\ v = 10.86\ v\) for an input current (electrons) of 10\(\mu\)a. This means that the positive range of the D/A will not all be used. In the negative direction (positive ion current) the maximum current will be even smaller, and is not expected to exceed 15% of the negative range capability.

The sense of the output code is arranged as follows: At the negative limit (-10v of positive ion current at B), all code bits are zero. As the current changes so as to move B in a positive direction, the code increases and at +10V all bits are 1.

At zero current (0 V at B) the code is

<table>
<thead>
<tr>
<th>DAC</th>
<th>ADC</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSB</td>
<td>LSB</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Here the ADC code is 200. It cannot be 0 for zero current because the upper level comparator excludes this point from the operating region. Therefore a major increment is "subtracted" (the DAC LSB = 0) and the ADC increased from 0 to 200.

The code/current algorithm is:

\[
i = [(\text{DAC} - 127)\ 200 + \text{ADC}] (5 \times 10^{-10})\]

where

- \(\text{DAC}\) = the decimal value of the D/a code
- \(\text{ADC}\) = the decimal value of the A/d code
- \(i\) = amperes (positive \(i\) means electrons flowing to the system. A negative \(i\) means positive ions flowing to the system).
- \(5 \times 10^{-10}\) = the resolution or amps/minor increment
When applied to the above code the result is:

\[ i = [(126 - 127) \times 200 + 200] \times (5 \times 10^{-10}) = 0 \]

If the current increases by a few minor increments, say 15, the lower level comparator will trip and the resulting code will be:

```
0 1 1 1 1 1 1 1 0 0 0 0 1 1 1 1
```

Applying the algorithm

\[ i = 15 \times (5 \times 10^{-10}) = 75 \times 10^{-10} \text{ a.} \]

The algorithm applies to all values of current.

In reading the value of the analog channel only 1 fact is necessary:

The gain of Amplifier 3 is exactly -0.5. If D is -6 v, F is +3v, etc.
If the ADC code is known the voltage at D and F can be computed. The ADC increment is 10v/256 = 39.0625 m.v. (40 mv is close enough). Therefore

\[
V_D = - (ADC) \cdot 0.04 \text{ volts} \\
V_F = (ADC) \cdot 0.02 \text{ volts} \\
or \ ADC = 50 \ V_F
\]

from which the algorithm can be applied,

\[ i = [(\text{DAC} - 127) \times 200 + 50 V_F] \times (5 \times 10^{-10}) \text{ amps} \]

III. The Interface Electronics

The Interface Electronics (IE) provides matching of the experiment output signal to the driver assembly and allows for operation of the DLP in different modes. In more detail the following functions are realized; we partly follow the schematic diagram. Fig. 4 and the timing chart Fig. 5.

1) The bit rate is to be provided by an external pulse generator. The word and frame rates are deduced from the bit rate.

2) The serial output signal DAC-ADC of the DLP is stored in a 16 bit storage register from where it will later be transferred
in parallel to the computer via 4 each quadruple 2-line to 1-line multiplexers.

3) The voltage of the internal or external bias generator is offset by +1.33V and then fed to an A/D-Converter. The A/D-Conversion is ordered by a strobe pulse generated in the programmer.

4) The converter is also used for A/D-Conversion of the probe position monitoring voltage (position sweep). This applies for the operation mode of the experiment, in which the probe is kept at constant bias voltage and moved within the plasma.

5) A set of eight toggle switches allows for monitoring the experiment number (EXPNO) or a coded STATUS in order to identify a particular data run (measurement).

6) Upon a select signal from the programmer the DAC/ADC data or the BIAS (or position)/EXPNO (or STATUS) data is alternately switched by the multiplexers to the driver assembly and then via optical couplers to the receiver section of the computer. Sixteen bits are transferred in parallel to the computer receiver but are not actually read into the computer until a cycle request pulse is generated by the programmer. The rate at which the data points are sampled is 366 per scan. It is independent from the scantime, since both, scantime and sampling period are fixed multiples of the bit period.

7) The programmer generated cycle request pulse commands the computer to read the data at its receiver inputs and to then follow the instructions given by the computer program for data storage and/or reduction.
IV. The Computer Software

At present the software for the I-P-Computer system consists of three programs:

1) Storage and Tape Transfer Program (PROBE), ASSEMBLER
2) Tape dumping Program (DLP), FORTRAN IV
3) Data Analysis Program (DIGITAL LANGMUIR PROBE), FORTRAN IV

PROBE handles the data flux that is coming from the DLP-experiment through the interface electronics IE to the receiver input of the computer. 16 bit data words are stored in the upper core memory and arranged in blocks of 8K Bytes. The part of memory used allows for storage of 22 blocks which form one file. One data block covers the data of 5.5 Scans of the Digital Langmuir Probe. As already mentioned the number of data samples taken per scan is 366 independently of the scan time. Thus with each run (measurement) practically 5 Langmuir Characteristics (each consisting of a full sweep upwards and a full sweep downwards) can be recorded. Prior to each measurement a computer attention button on the IE has to be pushed. This starts the computer to read 8 K bytes of data into the memory. A switch installed at the IE allows to interrupt the data flux.

Once up to 22 data blocks are stored they are transferred on to tape by executing PROBE with one label card for each block. The label card contains additional information (80 bytes) about the particular measurement such as file number, block number, date and experimental conditions (pressure, probe used, etc). The data sequence on tape is thus: label card information - data block label card information - data block - A.S.O. After each 22nd block an End of File (EOF) mark is written on the
tape. When executing PROBE for data transfer on to tape a 00 card inserted right after the label cards takes care of reinitializing the memory so that a new set of 22 measurements can be stored upon pushing the computer intention button.

For short compilation of the procedure in handling the program PROBE see the copy of the printer record in Appendix A.

The Program DLP reads the tape for a selected set of files and blocks and prints the data in 32 columns of octal numbers. The sequence of the data display is

\[
\text{EXPNO} - \text{ADC} - \text{DAC} - \text{BIAS}
\]

The selection of file Number (NF) and block (or record) number (NR) is made via a data card which contains the number of records to be read (MAXREX) in column 5, the number of records to be skipped (NRS) in column 10 and the number of files to be skipped (NFS) in column 15.

Fig. 6 shows the flow diagram for this program; a copy of the printer record of DLP is included in appendix B.

The program DIGITAL LANGMUIR PROBE in its present version meets the following objectives:

1) Skip a specified number of files and records and print label (or header) card.

2) Identify bias and find first bias peak. The bias identification relies on the fixed sequence of DAC/ADC/BIAS/EXPNO and the fact that the experiment number (toggle switch setting at the IE) is constant throughout one run.

3) Calculate current \( i \) out of DAC/ADC according to the algorithm given in Chapter II.
4) Calculate the derivative \( T_G = 11606.9 \frac{\Delta U}{\Delta \log i} \)

5) Print EXPNO, Bias, \( \log i \) and \( T_G \)

6) Plot data for one cycle (scan) on CALCOMP - Plotter

A simplified flow chart of this program is shown as Fig. 7, a copy of the program is included as appendix C.

Figs. 8 and 9 show two examples of Langmuir characteristics as semilogarithmic plots produced by the system. The current for increasing bias voltage is marked by x-es, for decreasing bias by squares. The ion current is plotted as log of its absolute value. The probe used in the plasma was a stainless steel sphere of 5 mm diameter. The surface was discharge cleaned for 10 minutes in nitrogen at about 10\( \mu \) pressure. The Langmuir curves show almost no hysteresis. In Fig. 8 the floating potential is at +100 mV. In this experiment the plasma was clearly non-Maxwellian since the differential or "generalized temperature" \( T_G \) shows a monotonous increase. Here crosses are for the upward going and triangles for the downward going part of the curve. Fig. 9 shows a case where the distribution function of the electrons is close to Maxwellian. This shows up in the shoulder shaped part of the \( T_G \) curve, occurring between 1 and 1.4 Volts and corresponding to an electron temperature \( T_e \) of about 5000 K. For an ideally Maxwellian distribution the shoulder would have a horizontal plateau. A high value of \( T_e \) corresponds to a large, a low \( T_e \)-value to a small horizontal extension of the plateau. The low \( T_G \)-values on the left side reflect the drop of the measured total current due to the ion current which becomes significant with decreasing bias voltage. The high \( T_G \)-values on the right side are due to the transition-knee from the retarding to the saturation regime of the
characteristic. This knee is influenced by the inhomogeneity of the work function over the probe surface. A perfectly homogeneous work function would produce a sharper knee of the electron current curve and a correspondingly straightened shape of the T_G-plateau.

Above 2.5 V bias the data are meaningless since in this case the current exceeded the upper current limit (10^{-5} amperes) to which the electronics of the Digital Langmuir Probe was set.

ACKNOWLEDGEMENT: The author is highly indebted to Dr. D. Winningham for providing the DLP back up electronics of the EQUION-project. Many thanks go to N. Eaker and C. Thompson for designing and building the interface electronics. The outstanding help from Dr. J. Midgley, L. Wadel and D. Beck in providing parts of the necessary software is particularly appreciated. The author finally wishes to express his gratitude to E. Milam for his engineering assistance.
DIGITAL LANGMUIR PROBE

FIG. 3
DLP tape dumping program

Fortran II

Reads tape, prints data in 32 columns of octal numbers - when decoded, disregard most significant binary digit.

FIG. 6
APPENDIX A

LIST TIM

TITLE PROBE

PROBE OPERATES SIMULTANEOUSLY WITH NORMAL BATCH PROCESSING.

IT ACCEPTS 16 BIT DATA WORDS, IN BLOCKS OF 4K WORDS, STORING THEM
IN UPPER MEMORY, AND (WHEN INSTRUCTED) DUMPING THEM ON TAPE AS A FILE.
A MAXIMUM OF 32 SUCH BLOCKS MAY BE STORED BETWEEN DUMPS.

WHEN PROBE IS RUN, ONE DATA (LABEL) CARD MUST BE INCLUDED FOR EACH
BLOCK TO BE WRITTEN. THE CONTENTS OF THE CARD ARE WRITTEN AS AN 80
BYTE LABEL WORD AND PREDECESSING THE 8K MTL DATA RECORD. THE FIRST TWO
DIGITS ON THE FIRST CARD SPECIFY THE FILE NUMBER, AND WHICH THE
BLOCKS ARE WRITTEN. A 80 CARD (CARD WHOSE FIRST TWO COLUMNS ARE ZERO)
FOLLOWING THE LAST LABEL CARD CLOSES THE FILE AND REINITIALIZES
MEMORY TO STORE ANOTHER 22 BLOCKS.

PROCEDURE 1
1) EXECUTE PROBE WITH ONLY A RR CARD, TO INITIAL MEMORY
2) PUSH ATTENTION BUTTON TO START DATA BLOCK
3) START DATA AND STOP IT AFTER 4K WORDS OR MORE,
4) REPEAT 2) AND 3), BUT NOT MORE THAN 22 TIMES.
5) EXECUTE PROBE WITH ONE LABEL CARD FOR EACH BLOCK TO BE
RECORDED ON TAPE, AND A 80 CARD TO REINITIALIZE MEMORY.
6) REPEAT 2)-5) AS OFTEN AS DESIRED, INCREASING FILE
NUMBER ON LABEL CARDS BY ONE EACH TIME.

GLOB TAPE

CALL, INIT, READ, WAIT, RLSE, EXIT

FILE IN: 1 THE ADDRESS WHERE INT IS STORED

PROBE1, INIT $LKR

161, HEAD $LKR, #CARD 1 READ ONE DATA CARD

WAIT $LKR

MOV A $0000

POP 164

POP 163

POP 162

POP 159

POP 158

POP 157

ADD A 1

POP 156

POP 155

POP 154

CPL H 65

CLI 118

DEC 64

BLE 35

MOV $40, NF

JSR $5, TAPE 1 SKIP NF FILES

BR 35

,WORD ONE

,WORD IC

,WORD IN

,WORD ZERO

,WORD NH

,WORD NF

REQ 64

128I, DUMP $120, NAS

MOV $120, NF

MVI $40, TAPE+64 1 SET NEW EXTENSION BITS

MVI $60, TAPE+72

JSR $5, TAPE 1 WRITE LABEL

BR 49

,WORD TWO

,WORD IC

;
APPENDIX B

TITLE: DLP

DLP DIRECTIONS:
USE DATA CARD TO SPECIFY RECORD READING
PUT NO. RECORDS, SKIP RECORDS, SKIP COL. 10, FILES SKIP COL. 15
REPEAT CARDS, USE 0 FOR MAXREX IN LAST CARD.

0001 BYTE BUFFER (8192), HEADER(80)
0002 EQUIVALENCE (BUFFER(1), HEADER(1))
0003 CONTINUE
0004 N = 0
0005 SKIP MODULE
0006 READ (4,1001) MAXREX, NRS, NFS
0007 1001 FORMAT (315)
0008 IF (MAXREX.EQ. 0) GO TO 7000
0009 IF (NFS.LE. 0) GOTO 5
0010 NB = 0
0011 NR = 50
0012 NF = 1
0013 CALL TAPE(-1,0,BUFFER,NB,NR,NF)
0014 NRS = NRS + 1
0015 GO TO 2
0016 CONTINUE
0017 IF (NRS.LE. 0) GO TO 10
0018 NB = 0
0019 NR = 2
0020 NF = 1
0021 CALL TAPE(-1,0,BUFFER,NB,NR,NF)
0022 NRS = NRS + 1
0023 GO TO 6
0024 10 CONTINUE
0025 1 N = 0
0026 IF (N .GT. MAXREX) GO TO 55
0027 CALL TAPE(-1,0,HEADER,NB,NR,NF)
0028 IF (NF.EQ. 0) GO TO 20
0029 IF (NB) 21, 28, 23
0030 WRITE (5, 541)
0031 541 FORMAT((IEND OF FILE))
0032 GO TO 22
0033 21 WRITE (5,542) N
0034 542 FORMAT((tape read/error on header, record=group, 17)
0035 GOTOC20
0036 23 WRITE (5,543) NB, N, HEADER
0037 543 FORMAT((header record short by: 13, ' record=group', 17 /
0038 1 (6I), 20A1)
0039 GOTOC20
0040 29 WRITE (5,555) HEADER, N
0041 555 FORMAT((01, 80A1, 20X, 'header record group', 17)
0042 C TEMPOARY: PRINTS OUT OCTAL FORM FOR DIAGNOSIS OF TAPE.
0043 WRITE (5,955) HEADER
IF(NF,NE,0) STOP
2 CONTINUE
WRITE (5,5701) MAXREX, NM, KX, IPI
5701 FORMAT(10MAX RECORDS*, 15,5X, RECORDS SKIPPED*, 15,5X*
1 MAX CYCLES PROCESSED PER RECORD*, 15,5X, PLOT CODE*, 13)
KX = 2 * KX - 1
C
IF(NH,LE,0) GO TO 5
NR = 0
NF = 1
CALL TAPE (-1, 0, BUFFER+ NB+NR,NF)
WRITE (5,5702) NH
5702 FORMAT(10AFTER SKIPPING, NR DECREMENTED TO*, 13)
5 CONTINUE
IF(KHCE,LE, MAXHEX) GO TO 888
C HEAD MDH RECORD, WAIT FOR COMPLETION
KREC = KHCE + 1
NR = 0
NF = 1
CALL TAPE (-1, 0, BUFFER+ NB+NR,NF)
C EF7
IF(NF,NE,1) GO TO 999
C HEAD EHHM ON SHORT RECORD?
C IF(NH) 10, 20, 30
C GOOD RECORD
20 CONTINUE
WRITE(3,5005) MH, KREC
5005 FORMAT(10, 72A1, 20X, RECORD NO.*, 15, ///)
C SAVE DATE FROM HEADER RECORD TO PLOT
DO 25 I = 1, 3
25 IDATE (I) = 1BUF (I+1)
C HEAD DATA RECORD, WT FOR COMP.
300 CONTINUE
NR = 8192
NF = 1
CALL TAPE (-1,0,BUFFER+ NB+NR,NF)
C EF7
IF(NF,NE,1) GOTO 999
C READ EHHM ON SHORT RECORD?
C IF(NH) 310, 320, 330
C GOOD RECORD
320 CONTINUE
C FIND PHASE
J = 3
DO 40 I = 6, 18*
IF(1BUF(2) .NE. BUF(I) .) GO TO 50
40 CONTINUE
DO 45 I = 602, 18*
IF(1BUF(2) .NE. BUF(I) .) GO TO 50
45 CONTINUE
GO TO 60
50 CONTINUE
J = 5
DO 55 I = 6, 20*
IF(1BUF(4) .NE. BUF(I) .) GO TO 70
55 CONTINUE
GO TO 60
50 CONTINUE
J = 7
DO 55 I = 6, 20*
IF(1BUF(4) .NE. BUF(I) .) GO TO 70
55 CONTINUE
GO TO 60
70 CONTINUE
CONTINUE

INTERM(1) = BUF(j-1)
EXPRN(1) = INTER
WRITE (5, 5015) EXPRN(1)

5015 FORMAT('DEXPONENT-NUMBER', 0S, 1) OCTAL')
C
CONTINUE

DO 80 J = J0+1, J1

INTERM (1) = BUF (1+3)
IF (INTERM = NE, EXPRN(1) ) GO TO 120
INTERM (1) = BUF (1+2)
BIAS (1) = INTERM
BYE = BS+SCALE=BIAS(1)
IF (BYE = GE. (P+AX-TOL)) GO TO 100

80 CONTINUE

120 CONTINUE

WRITE (5, 5020)

5020 FORMAT('PEAK NOT FOUND')

DO TO 4

100 CONTINUE

INTERM (1) = BUF (1 + 6)
IF (INTERM < LT. BIAS (1) ) GO TO 110
BIAS (1) = INTERM
I = I + 1
GO TO 100

110 CONTINUE

MAXIM (I) = 1 + 2
GO 210 I = 2, 6

210 MAXIM (I) = 0
DO 220 I = 2, 6

DO 220 J = JH, 2

MAXIM (I) = MAXIM (I-1) + 4 - LMIN
ITEMP = MAXIM (I-1) + 4 - LMAX
IF (ITEMP = GE. H(V) ) GO TO 230
INTERM (1) = BUF (ITEMP+1)
IF (INTERM = EQ. EXPRN(1) ) GO TO 240
INTERM (1) = BUF (INTERM + 1)
IF (INTERM = NE. EXPRN(1) ) GO TO 230

240 MAXIM (I+1) = ITEMP

220 CONTINUE

230 CONTINUE

C

TABULATE BIAS, DAC, ADC, F STARTING AT FIRST POSITIVE PEAK
C

DAC IS IN BUF (1+5)
ADC = BUF (1+4)
C

BIAS BUF (1+6)

EXPRN = BUF (1+7)

C

DO 200 K = 1, KK+2

KU = MAXIM (K-2)
IF (KU = EQ. 0) GO TO 5
KM = MAXIM (K+1)
KL = MAXIM (K)
LCTR = 99
N = 0
DO 400 KK = KK, KU, 1

N = N + 1
IF (KK = EQ. KM) NMID = N
INTERM (1) = BUF (KK-2)
ADC = INTERM
INTERM (1) = BUF (KK-1)
DAC = INTER

F(N) = ( (DAC - 127) * 200 + ADC ) * 5E-10
FABS = ABS (F(N) )
IF (FABS = EQ. 0) FABS = 1E-35
CUMLOG (N) = ALOG10 (FABS)
INTERM (1) = BUF (KK)

110 CONTINUE
BYAS (N) = BSCALE * BIAS(1) - OFFSET

C

INIT TE 50 CAN DETECT LATER IF ACTUALLY CALCULATED

TE (N) = 1.E-35

400 CONTINUE

NMAX = N

N = 0

DO 180 KK = KL, KU + 4

LCTH = LCTH +1

IF (LCTH .LE. 50) GO TO 130

LCTH = 0

WHITE (5, 5080)

5080 FORMAT(1*I8, I8, PT, BIAS, EXP#, DAC, ADC, CURRENT*,

1* LOG(CURRENT), DELTA_LOG, ADJ_BIAS, DELTA_BIAS*,

2* TE/)

130 CONTINUE

N = N + 1

KP = 1

IF ((K, .EQ., KL) .OR. (K, .EQ., KU)) KP = 2

INTERH(1) = HUF (K-2)

ADC = INTER

INTERH(1) = HUF (K-1)

DAC = INTER

BIAS(1) = INTER

ITEMP = NAV * 1

IF (N .LT. ITEM) GO TO 140

ITEMP = NMAX - NAV

DO 420 J = 1, NAV

JJ = NAV + 1 - J

FP = FINT + JJ

FM = FINT (N - JJ)

IF ((FP .GT. 0.) .AND. (FM .GT. 0.)) GO TO 430

420 CONTINUE

GO TO 140

430 CONTINUE

DCLOG = CUHLOG (N - JJ) - CUHLOG (N - JJ)

IF (DCLOG .LT. 0.) GO TO 140

BYAS = HYAS (N + JJ) - HYAS (N - JJ)

TE (N) = ABS ( TSCALE * BYAS / DCLOG )

WHITE (15, 5025) KK, N, BIAS(1), EXPN(1), PEAK(KP),

1/ DAC = ADC * F(N) * CUHLOG(N), DCLOG, BYAS(N), UBYAS, TE(N)

5025 FORMAT(*, 13* E13.5)

GO TO 180

180 CONTINUE

WHITE (15, 5025) KK, N, BIAS(1), EXPN(1), PEAK(KP),

1/ DAC = ADC * F(N) * CUHLOG(N), BYAS(N)

5025 FORMAT(*, 13* E13.5)

180 CONTINUE

IF (IFLT .EQ. 0) GO TO 200

IF (ISW .EQ. 0) CALL CALCMNP (12., 0., 0., 2)

ISW = 1

C

DRAW AXES

CALL XYAXES (EXPN(1), IDATE)

CALL PCLUH (CUHLOG, HYAS, NMID, NMAX)

CALL PLTEM (TE, BYAS, NMID, NMAX)

C

LET INK ON

CALL CALCMNP (0., 0., 0., 2)

200 CONTINUE

GO TO 5

5

C

10 CONTINUE

C

WHITE (5, 5110) XMEC

5110 FORMAT(*, I4, T10, HEAD-LUMIN, RECORD NO.*, 15I)
30 CONTINUE
20 STRUCT (15, 5130) NNU, KREC, NDH
5130 FORMAT (1X, ITAPE, RRECNO SHORT BY*, 10, 10X, 'RECORD NO.*', 15/
1")
40 GO TO 30
310 CONTINUE
10 STRUCT (5, 5110) KREC
20 GO TO 9
330 CONTINUE
10 STRUCT (5, 5330) NNU, KREC, BUF
5330 FORMAT (1X, ITAPE, RRECNO SHORT BY*, 18, 10X, 'RECORD NO.*
1157 (1, .3204))
60 GO TO 6
999 CONTINUE
10 STRUCT (15, 5999)
3999 FORMAT (1X, ITAPE, END-OF-FILE))
40 STOP
END
SUBROUTINE PICTIM (TN, HYAS, NMD, NMA)
REAL* HYAS(500), TEAS(500)
DATA C / 1.25 /
DATA D / 1.0 /
DATA IASMD / 91/
DATA ISYMHD / 92/
DATA IASM/ / 1.5 /
DATA H / 10.5 /
DO 100 I = 1, NMAX
C TRANSFORM ALL HYAS AS MAY NEED IN SUBRTN PICTIM
HYAS(I) = C * HYAS(I) * D
IF (HYAS(I) .LT. 1.75), DT, (HYAS(I) .GT. 6.75)) GO TO 100
IF (LHYAS(I) .LT. 5, 1.75), DT, (LHYAS(I) .LT. 6.75)) GO TO 100
LHYAS(I) = A * CULLOG(I) * R
ISYM = ISYMHD
TEAS(I) = IASMD
CALL SYMUL (HYAS(I), CULLOG(I), 0, 050, ISYM, 0, 0, -1)
100 CONTINUE
RETURN
END
SUBROUTINE PICTIM (TN, HYAS, NMD, NMA)
REAL* TEAS(500), HYAS(500)
DATA ISYMHD / 93/
DATA IASM/ / 44/
DATA A / 1.0 /
DATA H / 10.0 /
DATA CUT / 6.5 /
C CUT MUST CHANGE IF C .0 IN SUBRTN PICTUR CHANGE
C HYAS HAS BEEN TRANSFORMED BY IMMEDIATELY PREVIOUS CALL PICTUR
40 CC 100 I = 1, NMAX
C IF (HYAS(I) .LT. CUT) GO TO 100
C IF ((TEAS(I) .LT. 3.000000E+0) .OR. (TEAS(I) .LT. 100.)) GO TO 100
C TEAS(I) = A * ALUG10 (TEAS(I)) * R
C ISYM = ISYMHD
C TEAS(I) = IASMD
C CALL SYMUL (HYAS(I), TEAS(I), 0.050, ISYM, 0, 0, -1)
100 CONTINUE
RETURN
END
INTEGER IJUATE (3)
INTEGER NCD (5)
DATA ISYM / 31 /
DATA AL / 1.75 /
DATA YB / 3.5 /
DATA SCALE / 0.125 /
DATA CAN / 6.75 /
DATA TSCALE / 3.5 /
DATA CVSCALE / 1.5 /
DATA TL / 0.301039, 0.677121, 0.660206, 0.669897, 1.77815 /
1 0.845908, 0.90590, 0.954243 /
C
FPN = -1,
CALL NUMBER (AL=0.100, YB=0.500, 0.250, FPN=0.0 -1)
C
DUPLICATE TO ENSURE INK START
CALL NUMBER (AL=0.100, YB=0.500, 0.250, FPN=0.0 -1)
K = 0
CALL CALCMAP (AL= YB, 0.1)
DO 22 I = 1, 4
DO 18 J = 1, 9
K = K + 1
X = AL * K * ASYMBOL
CALL SYMBOL (X= YB, 0.14, ISYM, 0.0 -2)
18 CONTINUE
K = K + 1
X = AL * K * ASYMBOL
CALL SYMBOL (X= YB, 0.28, ISYM, 0.0 -2)
FPN = 1 - 1
CALL NUMBER (X=0.100, YB=0.500, 0.250, FPN=0.0 -1)
CALL CALCMAP (X= YB, 0.1)
22 CONTINUE
FPN = 10,
CALL NUMBER (X=0.25, YB=0.25, FPN=0.0 -1)
FPN = 2
CALL NUMBER (X009999 = YB=0.125, 0.15, FPN=0.0 -1)
CALL CALCMAP (X= YB, 0.1)
DO 2H I = 1, 3
J = 8
IF (I .EQ. 3) J = 2
DO 2H J = 1, J
Y = YB + TSCALE * (TL(J) - 1 - 1)
CALL SYMBOL (X= Y, 0.1, ISYM, 90, 0.0 -2)
28 CONTINUE
IF (I .EQ. 3) GO TO 2H
Y = YB + 1 * TSCALE
CALL SYMBOL (X= Y, 0.28, ISYM, 90, 0.0 -2)
FPN = 10,
CALL NUMBER (X=0.25, Y=0.25, FPN=0.0 -1)
FPN = 2
CALL NUMBER (X=0.25, YB=0.25, FPN=0.0 -1)
CALL CALCMAP (X= YB, 0.1)
28 CONTINUE
YSY = Y
FPN = 0,
CALL NUMBER (AL=0.75, YB=0.25, FPN=0.0 -1)
CALL CALCMAP (AL= YB, 0.0)
DO 3B I = 1, 5
5 DO 3A J = 1, 8
Y = YB + TSCALE * (TL(J) - 1 - 1)
CALL SYMBOL (X= Y, 0.14, ISYM, 90, 0.0 -2)
36 CONTINUE
Y = YB + 1 * TSCALE
CALL SYMBOL (X= Y, 0.28, ISYM, 90, 0.0 -2)
FPN = 1 - 9
CALL NUMBER (AL=0.75, Y=0.25, FPN=0.0 -1)