obviates these disadvantages of Langmuir probes. The original double probe system consists of two Langmuir probes similar in shape and size, which are connected to a variable potential source reversible in polarity. A double probe circuit permitting both point by point and automatic measurements is shown in fig. 6. The function relating the applied potential difference V_d to the current I_d measured in the external circuit, will be henceforward briefly be denoted by "DPC" (= double probe characteristic).

The current to each probe of the system is determined by the same equations which hold for single probes. In the case of electron retarding probe potentials we have therefore:

$$I_{e1,2} = \tfrac{1}{4} n_{01,2} e\bar{v}_{e1,2} A_{1,2} \exp \frac{eV_{p1,2}}{kT_{e1,2}}; \qquad V_{p1,2} < 0 \tag{83}$$

where the subscripts "1" and "2" refer to the two probes. In contrast to the behaviour of two single probes, the currents $I_{e1,2}$ are not independent of each other but are coupled by means of Kirchhoff's law:

$$I_d = |I_{+1}| - |I_{e1}| = |I_{e2}| - |I_{+2}|. \tag{84}$$

The potential difference between the two probes can be expressed in terms of their potentials with respect to the plasma in their vicinity:

$$V_d = V_{p1} - V_{p2} + V_c. \tag{85}$$

The potential V_c in eq. (85) takes account of the fact that the space potential as well as the contact potentials may be different for the two probes.

3.2. *The double probe characteristic*

Fig. 7 represents a DPC measured by means of the arrangement shown in fig. 6 in an electrodeless high frequency discharge. The symmetry of this DPC indicates that the probes which were used in this experiment are nearly equal in size and shape, and that they were located at positions where the plasma parameters are approximately equal. Looking at figs. 7 and 8 we easily understand the main features of such a symmetric double probe arrangement. There are four branches of the DPC, namely the two regions between the origin and the breaks E, E′ and the two slightly sloping portions between the points E′ and H′, and E and H. We denote the first by OE and E′O and the latter by H′E′ and HE. If the double probe is operated in the region H′E′ nearly no electrons reach probe 1, while the ions are attracted since $V_d \ll 0$ and according to eq. (85) $V_{p1} \ll V_{p2}$. The excess of ions flowing to probe 1 has to be balanced by an equal excess of

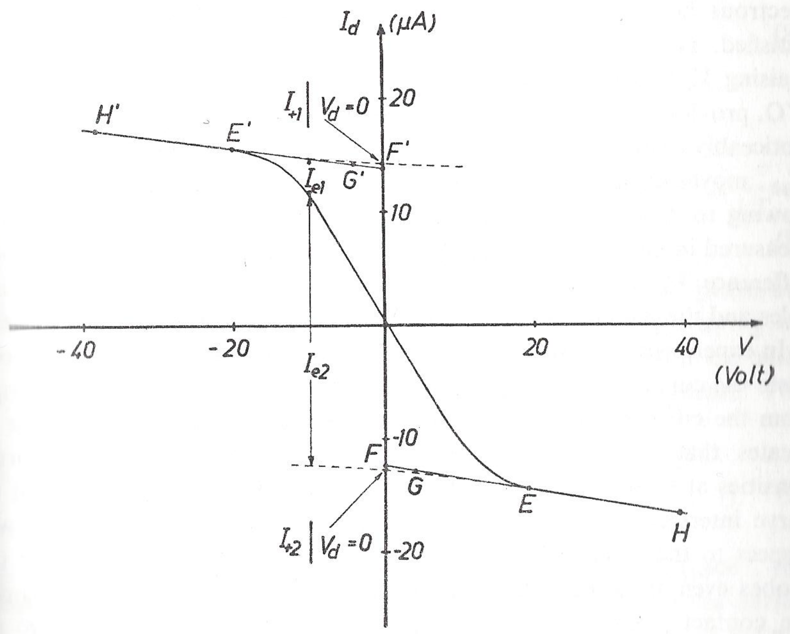

Fig. 7. Symmetric double probe characteristic.

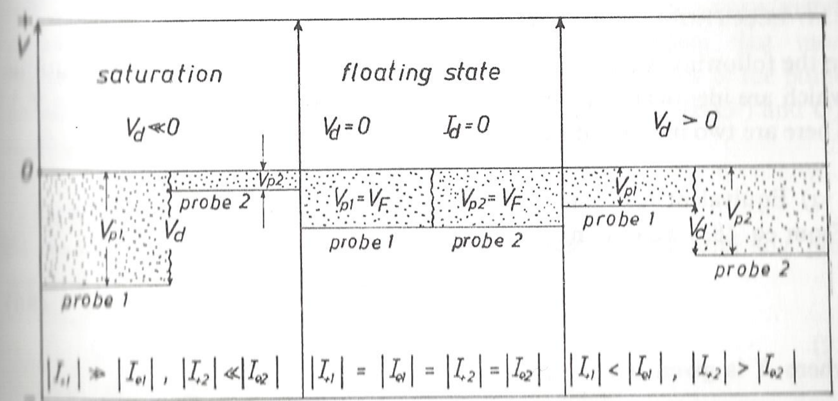

Fig. 8. Double probe potentials and currents of an idealized symmetric arrangement. The three columns (from left to right) correspond to the following branches or points of the characteristic (fig. 7): E′H′, origin, OH.

electrons flowing to probe 2, in order that Kirchhoff's law (eq. (84)) be satisfied. Hence probe 2 is positive with respect to floating potential. Raising V_d to more positive values ($V_d < 0$, however) we enter the region E'O, provided $-V_d < kT_e/e$. At this point the electrons begin to contribute noticeably to the current to probe 1. Simultaneously the potential of probe 2, V_{p2}, moves closer to the floating potential V_f and the excess of electrons flowing to it is decreased. In a symmetric probe arrangement the current measured in an external circuit I_d becomes zero, when the applied potential difference $V_d = 0$. At positive values of V_d the two probes change their roles and the regions H'E' and E'O' correspond to the regions HE and OE.

In experimental situations the DPC is frequently not symmetric. In some cases the curve goes through the origin, but its two branches left and right from the current axis are not equal in size and shape. This behaviour indicates that the collecting areas of the two probes or the charge carrier densities at their positions are different. In addition it may occur that the curve intersects the voltage axis at a potential positive or negative with respect to the origin. Hence a potential difference exists between the two probes even if no current is measured in the external circuit. In this case the contact potentials or the floating potentials of the probes are not equal or a potential gradient exists between points in the undisturbed plasma near the two probes.

3.3. *Evaluation of plasma parameters*

3.3.1. ELECTRON ENERGY DISTRIBUTION

In the following we assume that the electrons have Maxwellian distributions which are identical near the positions of the two probes ($T_{e1} = T_{e2} = T_e$). There are two important methods to evaluate T_e from the DPC.

α) Equivalent resistance method.
From eq. (83) we obtain:

$$\frac{I_{e1}}{I_{e2}} = K \exp\frac{eV_d}{kT_e}; \tag{86}$$

where K is given by:

$$K = \left[\frac{I_{e1}}{I_{e2}}\right]_{V_d=0} = \frac{n_{01}\bar{v}_{e1}A_1}{n_{02}\bar{v}_{e2}A_2}\exp\left(-\frac{eV_c}{kT_e}\right). \tag{87}$$

Differentiating eq. (86) with respect to V_d:

$$\left(I_{e2}\frac{dI_{e1}}{dV_d} - I_{e1}\frac{dI_{e2}}{dV_d}\right)\Big/ I_{e2}^2 = \frac{Ke}{kT_e}\exp\frac{eV_d}{kT_e} \tag{88}$$

and using eqs. (84) and (87) we have:

$$\left[\left(I_d\frac{dP}{dV_d} - P\frac{dI_d}{dV_d} + |I_{+2}|\frac{d|I_{+1}|}{dV_d} - |I_{+1}|\frac{d|I_{+2}|}{dV_d}\right)\Big/|I_{e1}I_{e2}|\right]_{V_d=0} = \frac{e}{kT_e}, \tag{89}$$

where P denotes the sum of ion currents flowing to the probe system at a given V_d. The ion currents do not change strongly with V_d near $V_d = 0$ compared to the electron currents near this point. Terms which are multiplied by derivatives of the ion currents therefore may be neglected. Thus we arrive at a simple expression for T_e:

$$T_e = -\frac{e}{k}\left[\frac{|I_{e1}I_{e2}|}{P}\frac{dV_d}{dI_d}\right]_{V_d=0}. \tag{90}$$

The quantity $|dV_d/dI_d|_{V_d=0}$ which is called "equivalent resistance", represents the slope of the DPC, at the point, where it intersects the current axis. In addition the sum of ion currents P at $V_d = 0$ has to be known. If we should evaluate this quantity by linear extrapolation of the portions H'E' and HE to their intersection points with the I_d-axis (points F and F' in fig. 7), we should arrive at too low a value of P at $V_d = 0$. As pointed out in [9] the functions $I_{+1,2}(V_{p1,2})$ can be approximated by straight lines but this is not true for the functions $I_{+1,2}(V_d)$. In the case of approximately symmetric characteristics Johnson and Malter have shown that more correct values of $(I_{+1,2})_{V_d=0}$ can be gained from the ordinates of the points G' and G in fig. 7. The ratio between the distances FG (F'G') and GE (G'E') has to be 1 : 4.

β) Semi log plot method.
From eq. (86) an expression similar to that used in the semi log plot method for single probes can be derived:

$$d\ln\left(\frac{I_{e1}}{I_{e2}}\right)\Big/dV_d = \frac{e}{kT_e} \tag{91}$$

which can be rewritten with the aid of eq. (84)

$$d\ln\left(\frac{P}{|I_{e2}|} - 1\right)\Big/dV_d = \frac{e}{kT_e}. \tag{92}$$

This method does not depend very sensitively on the choice of the values of P, since an error in P leads to an error in I_{e2} in the same direction as we see from a glance at fig. 7. In the case of a Maxwellian distribution of the electrons the plot $\ln (P/I_{e2}-1)$ versus V_d yields a straight line with the slope e/kT_e. In contrast to the single probe method deviations of the semi log plot from linearity do not always indicate the presence of non-Maxwellian electron energy distributions. These deviations may also be due to a difference in electron temperatures in the vicinity of the two probes. Assuming the electron temperature at probe 1 is larger than at probe 2, the mean electron temperature $\overline{T}_e = \frac{1}{2}(T_{e1}+T_{e2})$ can be calculated from the slope of the semi log plot at $V_d = 0$:

$$dV_d/d\ln\left(\frac{P}{|I_{e2}|}-1\right) = \frac{k}{e}\left[\overline{T}_e+\Delta T\left(\frac{1-K}{1+K}\right)\right]\bigg/\left(1-\frac{k}{e}\Delta T\frac{d\ln(P^2/C_1C_2)}{dV_d}\right) \tag{93}$$

with

$$\Delta T = \tfrac{1}{2}(T_{e1}-T_{e2}); \qquad C_{1,2} = \tfrac{1}{4}n_{01,2}e\bar{v}_{e1,2}A_{1,2}. \tag{93a}$$

The terms in round brackets describe the deviation of the measured "electron temperature" from $\overline{T}_e$. Since P does not depend strongly on V_d and the term $(1-K)/(1+K)$ never exceeds unity, the error in the evaluation of $\overline{T}_e$ is not larger than ΔT.

3.3.2. CHARGE CARRIER DENSITY

It is useful to remember that the ion currents measured with the double probe are obtained as functions of the applied voltage V_d and not as functions of the probe potentials $V_{p1,2}$. At sufficiently high values of $V_d(|V_d| \gg kT_e/e)$ one probe e.g. probe 1 is always situated near space potential, while the other, 2, is strongly negative with respect to space. The ion current flowing to 2 varies only slightly with probe potential and has to be balanced by a resultant electron current to 1, which exhibits an exponential dependence on probe potential. Hence for large values of $|V_d|$ we have:

$$I_{+2}(V_d) \cong I_{+2}(V_{p2}). \tag{94}$$

Using the ion current formula, which is valid for the parameter range under investigation (see sect. 2.3.2) we are able to evaluate the charge carrier density from the current in the region of the DPC where relation (94) holds.

In order to minimize the errors involved in this method (and also in the equivalent resistance method) it is desirable that the ion current depends as weakly as possible on V_d. Spherical probes for which the ion current saturation is poor should not be used in double probe arrangements.

4. Probes under complicated plasma conditions

4.1. *High pressure*

The low pressure theory fails, if one or both of the conditions $r_p \ll \lambda$ and $h \ll \lambda$ are not satisfied. The physical meaning of the inequality $r_p \ll \lambda$ was already considered in sect. 2.3.1.2. Collisions within the space charge sheath have to be taken into account if $h \gtrsim \lambda$. We now treat some important limiting cases of the parameter range of this section:

4.1.1. $r_p \gg \lambda, \quad h \ll \lambda$

Under the assumptions of this paragraph the electric field, grad V, of the probe in a distance from the surface larger than λ is very weak, so that the mobilities $\mu_{+,e}$ of the two charge carrier species can be assumed to be independent of grad V. This assumption is valid as long as the energy gained by a particle between two successive collisions does not exceed its initial energy:

$$e\lambda\,|\operatorname{grad} V| < \tfrac{1}{2}kT. \tag{95}$$

This relation is not fulfilled, when $h > \lambda$. In our case the current to a probe is determined by the macroscopic transport equations and orbital motion of the particles can be neglected. The basic equations read:

diffusion: $$\Gamma_{+,e} = -D_{+,e}\operatorname{grad} n_{+,e} \mp n_{+,e}\mu_{+,e}\operatorname{grad} V \tag{96}$$

where $\Gamma_{+,e}$ are the particle current densities and $D_{+,e}$ the diffusion constants;

continuity: $$\operatorname{div}\Gamma_{+,e} = n_{+,e}\beta \tag{97}$$

where β is the ionization frequency (volume recombination is neglected);

and Poisson's equation: $$\Delta V = \operatorname{div}\operatorname{grad} V = -4\pi e(n_+ - n_e). \tag{98}$$

Under the simplifying assumptions: constant mobilities and diffusion coefficients, no recombination or production of carriers in the region perturbed by the probe, no Coulomb collisions, infinite plasma and no influence of the probe on the neutral particles, the probe in a collision dominated plasma has been treated by means of mathematical methods similar to those