Ion Energy Distribution at the Wall of a Non-Thermal Plasma

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A combined mass spectrometer — probe diagnostic is applied to investigate the energy distribution of positive ions at the wall of a positive column in Argon. With a small wall probe, perforated for ion extraction, the probe characteristic, the A$^+$-current versus probe potential, and the A$^+$-current versus retarding potential are measured. Electron temperature from the probe characteristic and ion temperature from the last two characteristics agree within the experimental error. The Bohm criterion can be modified by $T_+ = T_e$ at the wall. With a small wall probe the sheath only partly can be reduced; for positive probe potentials a potential wall in front of the probe is built up, which acts as an energy analyzer. Ion-neutral and ion-ion collisions cannot account for the Maxwellian distribution of the ions found experimentally.

1. Introduction

In probe diagnostics and mass spectrometry ions coming from a plasma to a metallic or a glass wall are investigated. In front of the wall the ions pass the sheath, which changes their density and energy. This influence of the sheath has to be known, if plasma parameters shall be deduced from the measured data at the wall. Especially in mass spectrometry, inelastic collisions between ions accelerated in the sheath and the neutral background gas may produce new species.

Within the sheath a field, produced by a positive space charge, accelerates the ions and decelerates and reflects the electrons; thus at an isolated wall the thermal electron current becomes equal to the ion current. The ions, entering the sheath, possess a velocity $v_{+\perp}$ normal to the wall, satisfying the Bohm criterion[1]:

$$\frac{m_+}{2} v_{+\perp}^2 \geqq \frac{1}{2} kT_e , \qquad (1)$$

m_+: mass of the ions,

T_e: temperature of the electrons.

This expression holds for monoenergetic ions. Considering a velocity distribution of ions, entering the sheath, this criterion may be written in form of Eq. (2a) (Harrison and Thompson[2]; Cavaliere, Engelmann and Ognori[3]; Riemann[4]):

$$\left\langle \frac{1}{\frac{m_+}{2} v_{+\perp}^2} \right\rangle^{-1} \geqq kT_e/2 , \qquad (2a)$$

$$= kT_e/2 , \qquad (2b)$$

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where the authors[3,4] show, that this criterion marginally holds (Equation (2b)). The ions gain the necessary velocity $v_{+\perp}$ within a presheath, located between the plasma and the sheath. The main properties of this plasma wall transition is shown in Table 1. With respect to the plasma parameters in our application we have assumed a collisionless sheath and a collision-dominated presheath. Riemann[4] shows, that the Bohm criterion (2b) actually can be interpreted as a definition of the edge between sheath and presheath.

Within the plasma ions are transported from the place of their production towards the wall by ambipolar diffusion, the radial electric field and thus the ion temperature increase. Within the presheath the ion velocity distribution becomes directed, due to the high field. In case of resonant charge transfer practically a one dimensional velocity distribution enters the sheath suffering an additional acceleration.

Measurements of the ion energies $m_+ v_{+\perp}^2 / 2$ at the wall of a low pressure positive column showed approximate Maxwellian distributions with a temperature of the order of T_e (Henrich and Müller[5]). The calculations of Riemann[4] assuming resonant charge transfer resulted in pronounced non-Maxwellian distributions with the average ion energy of kT_e.

Thus the plasma wall transition in a non-thermal plasma still is problematic. Because of its importance for diagnostics we resume this problem. With a combined mass spectrometer–probe diagnostic we investigate the energy distribution of positive ions at the wall.

A small perforated electrode within the glass wall, shortly wall probe, serves as a Langmuir

Table 1. Plasma wall transition.

	sheath	presheath	plasma
function with respect to the wall currents	equilibration of ion and thermal electron currents to the wall	heating up of the positive ions (Bohm criterion)	source of electrons and ions
characterization	collisionless positive space charge region	collision dominated quasineutral plasma with high electric field	collision dominated quasineutral plasma with low electric field
length parameter	Debye length λ_D	mean free path of the ions λ_+	radius R of the plasma

probe to measure probe characteristics and as an extraction electrode for mass spectrometry of positive ions. A grid inside the mass spectrometer allows an energy analysis of the ions. Three different characteristics have been measured:

— probe characteristic:
  probe current versus probe voltage,
— ion characteristic:
  current of a special ion to the mass spectrometer versus probe voltage,
— retarding field characteristic:
  current of a special ion to the mass spectrometer versus retarding voltage for a fixed probe voltage.

The probe characteristic provides the electron temperature. An analysis of the retarding field characteristic results in a Maxwellian distribution of the energy $m_+ v_{+\perp}^2/2$ of the ions with electron temperature. A simple analysis of the ion characteristic gives the same result.

These experimental results can be summarized in a modified Bohm criterion:

$$T_+ = T_e \quad \text{(at the wall)} . \tag{3}$$

The ion characteristic provides an additional diagnostic tool to measure the electron temperature via the ion temperature at the wall. The interpretation of our results gives a new understanding of a wall probe.

2. Basic Considerations

We investigate the non-thermal plasma of a positive column by a combined mass spectrometer–probe diagnostic (see Fig. 1) using a small wall probe, the sheath of which is surrounded by the sheath of the glass wall. The discharge parameters are chosen such that for the characteristic lengths

the following conditions hold:

$$d, R_b \ll \lambda_+, \ R_p \ll R , \tag{4}$$

R: radius of the plasma (14 mm),
R_p: radius of the wall probe (0.3 mm),
R_b: radius of the bore within the wall probe (0.025 mm),
d: depth of the bore (0.05 mm),
λ_+: mean free path of the ions (0.1−1 mm).

An estimate of the Debye length gives a value of the order of the mean free path of the ions. How-
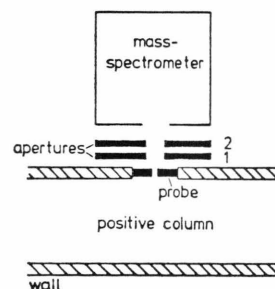

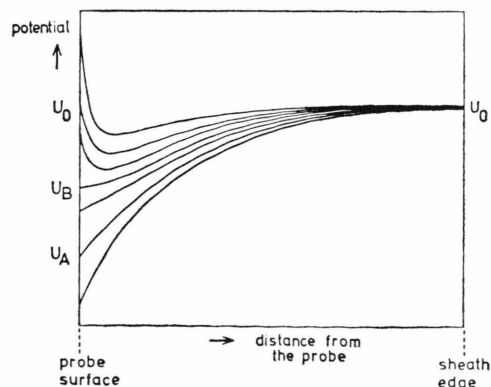Fig. 1. Combined mass spectrometer — probe diagnostic of a positive column.

Fig. 2. Schematic potential distribution in front of a small wall probe for different probe potentials.

ever, the analysis of our experimental results confirm the model of a collisionless sheath in front of the probe.

It is the aim of this section to develop an understanding of the sheath-in-sheath problem occurring in front of a small wall probe and to provide a basis for the interpretation of our experimental results.

Figure 2 shows schematically the potential distribution in front of a small wall probe for different probe potentials. At the potential U_A the probe floats, the net current to the probe vanishes. With increasing probe potential the sheath voltage is decreased, until the situation U_B of vanishing field at the probe is reached. For a probe located in the plasma this is the case, when the probe potential is equal to the plasma potential. Here the analytical description of the electron current to the probe changes, which influences the shape of the probe characteristic. For high probe potentials a potential wall in front of the probe is built up, which finally exceeds the potential U_0 of the sheath edge and reflects ions from the plasma. Further increase of probe potential mainly changes this potential wall. For a larger wall probe the situation U_B of vanishing field occurs at higher probe potentials.

Actually the potential distribution in front of the probe changes in radial direction parallel to the probe. Due to this radial effect the incoming ions show converging paths for ion attraction (see Fig. 3) or diverging paths for ion repulsion. Therefore the effective probe radius $R_{p\,eff}$, determining the probe current, changes with probe potential.

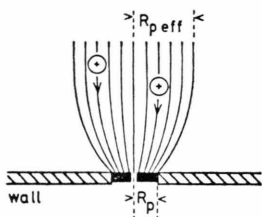Fig. 3. Ion paths in front of an ion attracting probe; R_p: probe radius, $R_{p\,eff}$: effective probe radius, due to the converging paths.

If this influence of variable effective probe radius can be neglected, an ion energy analysis is possible by a variation of the probe potential, due to the reflection at the varying potential wall.

3. Experiment

3.1. Apparatus

A schematical view of the apparatus is given in Figure 4. Ions are extracted by the wall probe and focused to the entrance of a quadrupole mass spectrometer by two electrostatic apertures. With this set-up neutrals, positive and negative ions can be investigated. A grid within the mass spectrometer allows an energy analysis of the ions. By differential pumping a pressure better than $2 \cdot 10^{-6}$ Torr was achieved within the mass spectrometer.

Measurements have been performed under flowing gas conditions. Before a measuring cycle the discharge had been run for $1-2$ hours.
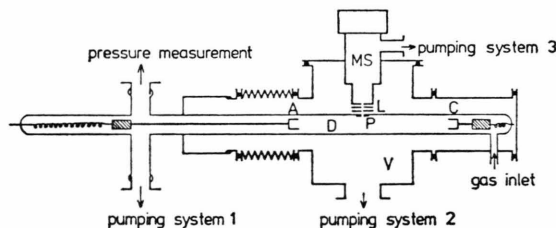

Fig. 4. Schematic view of apparatus.
D: discharge tube (Pyrex),
C: cathode,
A: anode,
P: perforated wall probe,
L: lens, consisting of two apertures,
MS: quadrupole mass spectrometer (Micromass Q 50),
V: vacuum vessel,
pressure measurement: capacitance manometer (MKS Baratron).

3.2. Ion Extraction and Energy Analysis

The ion extraction from a plasma to a mass spectrometer is discussed in the review papers of Hasted[6], Märk and Helm[7]. Following problems are relevant for our application.

In analysing of the ion current to the multiplier one has to take into account ion production outside the plasma, due to electron collisions, and transmission losses of the ions on their path from the sheath edge through the bore, the apertures 1, 2 and through the mass spectrometer. As a reference situation one may consider the case, where ions with only a velocity component $v_{+\perp}$ normal to the wall enter the sheath, are accelerated in a plane sheath, leave the bore as a parallel beam and pass the total ion-optical system between wall probe and multiplier in its axis. In this ideal situation no transmission losses occur. In the following, devia-

tions from this situation shall be discussed, giving rise to additional ion production and to transmission losses, due to a non-vanishing velocity component $v_{+\parallel}$ parallel to the wall.

In the high electric field of the presheath a practically one dimensional velocity distribution with only $v_{+\perp}$-components is formed, if resonant charge transfer collisions dominate. However in the case of A^+-ions in its parent gas a significant fraction of elastic scattering occurs, and a three dimensional velocity distribution is built up. The influence of a $v_{+\parallel}$-component is reduced by the acceleration and enhanced by collisions within the sheath.

A plane sheath in front of the wall probe exists for a probe potential U_p equal to the potential U_w of the surrounding wall, if one neglects the curvature of the wall. For a large probe, $R_p \gg \lambda_D$, a plane sheath may be assumed for potential differences $|U_p - U_w|$ of the order of kT_e/e. Generally a curved sheath with converging or diverging ion paths (see Fig. 3) has to be taken into account.

For high pressures collisions of the electrons with the neutrals within and beyond the bore occur. Due to this effect this region may serve as an electron impact ion source for the detection of neutrals (Pahl, Lindinger, Howorka[8]). This effect may be tested by sampling ions in the electron attraction part of the probe characteristic. In our application this effect has not been observed.

The high field of the sheath, especially in the ion attraction part of the probe characteristic, may penetrate the bore. Due to an ion-optical effect such a field penetration produces a velocity component $v_{+\parallel}$ and only can be avoided by a field in the outer region, which is approximately equal to the field within the sheath. Experimentally this is done by a suitable choice of the potential of the aperture 1 (Fette[9], Zwirner[10]).

3.3. Preliminary Experiment

For the evaluation of the ion characteristic and the retarding field characteristic those effects are of importance which change the transmission along a characteristic. To investigate this a preliminary experiment has been performed.

The ion current to the multiplier has been optimized by a suitable choice of the electrostatic lenses inside and outside the mass spectrometer. These potentials remained fixed during the measurement of all characteristics of a given plasma.

The constancy of the transmission of this situation has been tested by analyzing a distribution of ions from the sheath edge after accelerating it by different sheath voltages. For a constant transmission, energy distributions, shifted by the change of the sheath voltage, are expected. To avoid the influence of a curved sheath a large probe radius ($R_p = 3.5$ mm) has been chosen. The pressure of 0.45 Torr provided stationary plasma conditions at the one hand and a possible influence of collisions in the sheath at the other hand. The selected probe currents belonged to that part of the probe characteristic where the investigated ions are decelerated and accelerated moderately.

In Fig. 5 the test measurements are shown. As for a collisionless plane sheath can be expected a set of energy distributions results, shifted by voltage differences, which within the limit of experimental error coincide with the differences of the probe potential. The ions, represented by the distribution $-I_p = 440\ \mu A$, may be regarded as test ions. After accelerating them transmission losses occur in the low energy part of the distribution, the high energy part remains unchanged. Therefore the energy analysis has to be restricted to the high energy part of the distribution. An optimal situation can be found at negative probe currents. For changed probe radius and pressure the energy analysis has been checked by such test measurements.
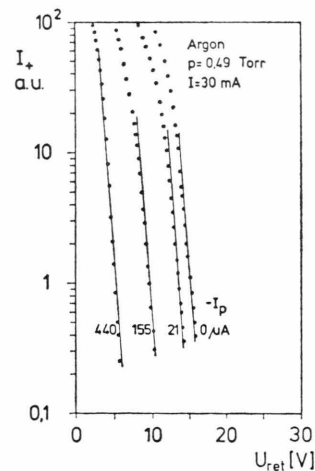

Fig. 5. Test measurements of energy distributions for different probe currents.
○ : measurements,
— : set of shifted distributions, fitted to the measurements.

3.4. Experimental Results

Measurements have been made with a small probe ($R_p = 0.3$ mm) at the positive column in
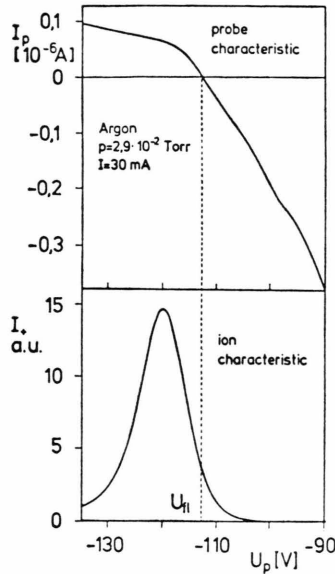
Fig. 6. Probe characteristic (upper curve) and A^+-characteristic (lower curve) for a positive column in Argon; U_{fl}: floating potential $(I_{\mathrm{p}} = 0)$.

Argon for pressures $2 \cdot 10^{-2}$ Torr $\leq p \leq 1$ Torr and discharge currents 30 mA $\leq I \leq 90$ mA. The dominating ion A^+ has been investigated. In the following figures representative curves are shown.

In Fig. 6 a probe characteristic and the corresponding ion characteristic are shown. The electron current to the probe, found by an analysis of the probe characteristic and the right part of the ion characteristic, are plotted logarithmically in Figure 7. A retarding field characteristic $\log I_+$ versus U_{ret} for a probe voltage of -110 V is given in Figure 8. The influence of the probe voltage on the retarding field characteristic can be seen from Fig. 9 for a slightly changed pressure.

Similar results in the same plasma have been found with the large probe ($R_{\mathrm{p}} = 3.5$ mm). However, the temperatures $T_+ = T_{\mathrm{e}}$ were reduced by a factor of about 4, due to the perturbation by the large probe.

4. Discussion

We start with an analysis of the probe characteristic in Figure 6. For high negative probe voltages the ion current linearly depends on the probe voltage. This dependence is the same as for a spherical probe in the case of orbital limited motion (see e.g. Chung, Talbot and Touryan[11]). The slope
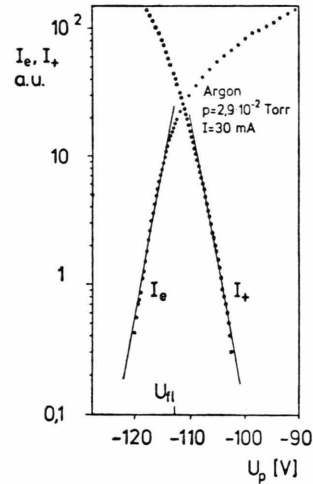

Fig. 7. Electronic part of the probe characteristic and A^+-characteristic in the ion repelling region, taken from Fig. 6, giving $T_{\mathrm{e}} = 2.0$ eV, $T_+ = 2.2$ eV.
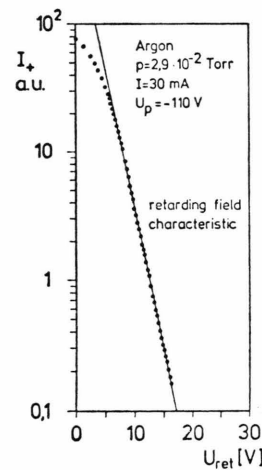

Fig. 8. Retarding field characteristic, giving $T_{\mathrm{ret}} = 2.1$ eV.

is due to the increase of the effective probe radius with decreasing probe voltage.

The logarithmic plot of the electron current in Fig. 7 is linear in the electron repelling region of the probe characteristic and corresponds to a Maxwellian energy distribution of the electrons. For a common probe characteristic the plasma potential is characterized by a transition of the electron current from saturation to retardation by field, the analytical description changes. For the wall probe this change occurs for the situation of vanishing field at the probe, demonstrated by the curve U_{B} of Figure 2.
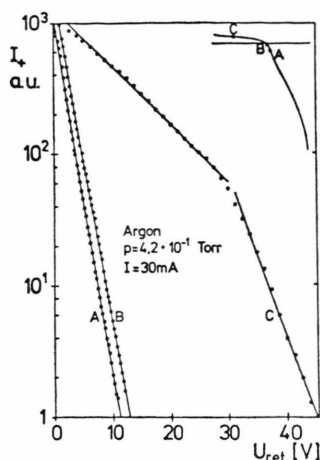
Fig. 9. Retarding field characteristics for different probe potentials, the locations of which in a qualitative probe characteristic are shown in the upper right part.

The characteristic of a wall probe shows, compared to that of a probe in a plasma, a higher ratio of thermal ion and electron current. This is due to the sheath-in-sheath configuration leading to the potential curves of Fig. 2 with the special "plasma potential situation" of curve U_B.

With decreasing probe voltage the ion characteristic of Fig. 6 passes an ion repelling region with an exponential increase and an ion attracting region with a maximum and a decrease, due to transmission losses. These may be attributed to a curved sheath, to field penetration, or to collisions within the sheath. In the ion repelling region the potential wall in front of the probe acts as an energy analyzer. The corresponding energy analysis leads to a Maxwellian energy distribution of the ions possessing a temperature equal to the electron temperature found from the probe characteristic.

The retarding field characteristic of the ions (Fig. 8) in the ion repelling region gives the same temperature as the two other independend methods.

The influence of the working point on the retarding field characteristic is demonstrated in Figure 9. The location of the working points A, B, C on a schematic probe characteristic is shown in the upper part of the figure. Within the ion repelling region (curves A and B) the retarding field characteristics are straight lines of the same temperature. In the ion attracting region (curve C) a retarding field characteristic results, which might be approximated by two straight lines. The upper part is dominated by transmission losses. The lower part

shows an increased temperature which may indicate that with increasing sheath voltage the field within the presheath is increased and produces a higher ion temperature.

If a measurement of the ion temperature by this method shall provide the electron temperature, the working point A has to be chosen.

Table 2. Electron temperature T_e taken from the probe characteristic, and ion temperatures T_+, T_{ret}, taken from the ion characteristic and the retarding field characteristic, for different pressures *. Discharge current: 30 mA.

p [Torr]	T_e [eV]	T_+ [eV]	T_{ret} [eV]
$1.8 \cdot 10^{-2}$	2.0	2.1	2.1
$2.9 \cdot 10^{-2}$	1.9	1.9	2.0
$2.0 \cdot 10^{-1}$	1.4	1.3	1.3
$6.0 \cdot 10^{-1}$	1.3	1.3	1.3
1.0	—	1.0	1.0

Table 2 lists the temperatures found by the three independent methods for different pressures. The three methods lead to the same temperature. Thus the measurement of the ion temperature at the wall provides a possible method to determine the electron temperature. The investigation shall be extended to plasmas in other gases.

Still open is the problem, what mechanism gives rise to the Maxwellian energy distribution of the ions, entering the sheath. Ion-neutral and ion-ion collisions cannot account for this mechanism. Therefore we have to postulate an additional interaction mechanism of the ions.

With respect to mass spectrometry of positive ions from a plasma the following conclusions can be drawn. By a small wall probe the sheath only partially can be reduced. With increasing positive probe potential a potential wall in front of the wall is built up, which reflects incoming ions. The ions, coming from the presheath, possess a Maxwellian energy distribution, determined by the electron temperature and being shifted by the acceleration via the sheath. By a large wall probe the electron temperature and thus the ion temperature at the wall is changed severely. An alternative method consists in ion sampling through an aperture, the

* For $p = 1$ Torr the evaluation of the probe characteristic became problematic, due to the decreased mean free path of the ions.

bore of which is large compared to the Debye length. Here the plasma flows through the aperture and expands, until an extraction is possible without any sheath.

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