ELECTROSTATIC PROBES FOR THE INVESTIGATION OF ARC-DRIVEN ELECTRIC PROPULSION DEVICES

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Abstract

For the development of electric propulsion devices, the investigation of fundamental plasma parameters is essential in order to improve the knowledge of the physics. Electron temperatures, electron densities, plasma potentials and electron energy functions of plasma jets generated by magnetoplasmadynamic devices and thermal arcjets are obtained by cylindrical electrostatic single-, double- and triple-probes. The probes are operated in the collisionless regime, using Laframboises theory applicable for probes aligned with the plasma stream. The measured values of electron temperatures and densities show reasonably good agreements for all types of probes within ± 15% of the measured values. Single-probe measurements of the electron temperature are mainly affected by deviations of the theoretically assumed Maxwell electron energy distribution, whereas triple-probe results are influenced by large variations in the ion current densities of small plasma plumes compared to the probe dimension. Plasma velocities are determined with time of flight probes whenever natural fluctuations of the ion current densities occurred. Pressure calculations using the Bernoully equation and the results, especially in the plasma wind tunnels, compare very well with measured pressures of a Pitot probe. Without natural fluctuations, the velocity is obtained by relating the ion current of two single-probes, oriented perpendicular and parallel to the plasma stream, to the ratio of directed and thermal ion velocities according to the theory of Kanal. Therefore the ion temperature must be known to calculate the thermal velocity. Otherwise the ion temperature can be estimated with this method, if the directed plasma velocity is known, for example by time of flight measurements. Since this theory is only applicable to probes aligned with the plasma stream, the plasma flow field must be known. This is obtained by the shape of the ion current to a rotating single-probe at a specific position in the plasma jet. Since this method is limited to regions of low thermal loads on the probe, a new method to detect a specific plasma streamline was developed. By moving radially through the plasma plume, the ratio of the current to a cylindrical single-probe oriented at a specific angle to the plasma and the current to a plane probe unaffected by angles of attack yields the radial position of the plasma streamline with the same angle as the single-probe.

Nomenclature

A	Area of probe electrode
e	Electron charge = $1.6021892\ 10^{-19}$ C
I	Probe current
I_e	Electron-current
i_i	Ion-current
i_i	Ion-current correction factor
j_e	Electron-current density
j_i	Ion-current density
Kn	Knudsen number = λ_{xx}/r
k	Boltzmann-constant = $1.380662\ 10^{-23}$ J/K
l	Probe-length
m_e	Electron-mass
m_i	Ion-mass
n_n	Neutral particle density
n_o	Charged particle density
n_e	Electron-density
n_i	Ion-density
R_v	Velocity ratio = v/v_{th}
r	Probe radius
s	Plasma sheath radius
T	Temperature
T_e	Electron-temperature
T_i	Ion-temperature
V	Applied external probe-potential
V_F	"Floating"-potential
V_{PL}	Plasmapotential
V_d	Potential-difference between two electrodes
v	Directed velocity of plasma particles
v_{th}	Mean thermal velocity
v_i	Directed Ion-velocity
α_s	Fixed probe angle to the plasma jet axis
β	Triple-probe correction factor
χ_p	Normalized probe potential = $e(V_{PL}-V)/kT_e$
δ_p	Angles betwen the plasma streamlines and plasma jet axis
$\Gamma()$	Gamma-function
θ	Angle off attack between probe and plasma flow
λ_D	Debyelength, $(\varepsilon_o kT_e/e^2 n_e)^{1/2}$
λ_{xx}	Mean free path of charged particles, (xx=ei, ee, ii)
λ_f	Mean free path of neutrals
τ_l	"End"-Effect-parameter

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Introduction

At the Institut für Raumfahrtsysteme (IRS) of the University of Stuttgart, stationary thermal arcjet thrusters (TAT) in the power range of 1 to 100 kW and MPD-self-field thrusters of up to 1MW are under development and the possible application as thrusters for space vehicles is investigated [1]. Based on the experience with MPD thrusters, a nozzle type device was modified for operation as a plasma source (MPG) for reentry simulation facilities [2]. The properties of the plasma plumes of the thrusters and the MPG are experimentally investigated by optical means [3], mechanical probe methods [4,5], mass spectroscopy [6,7] and a variety of electrostatic probe methods [8]. This paper will give an overview of the applicable electrostatic probe methods which are listed below:

Single-probes:	Electron temperature T_e, Electron density n_e, Plasma potential V_{PL}, Electron energy distribution function $F(\varepsilon)$.
Double-probes:	Electron temperature T_e, Ion density $n_i = n_e$.
Triple-probes:	Electron temperature T_e, Electron density n_e,
Time of flight:	Ion velocity v_i.
Crossed single probes:	Ion velocity v_i, Ion temperature T_i.
Rotating single probes:	Streamlines angles δ_p
Fixed angle single-probes:	Streamline positions $y(\delta_p)$.

For all types of probes cylindrical probes are used, except for the fixed angle-probe which includes also a plane probe-electrode as described later in this paper.

Probe theories and plasma properties

Although electrostatic probes are experimentally relatively simple devices, the applicable theory to describe the probes response could be very complicated [9-11]. This is mainly caused by the influence of the probe electrode on the plasma properties. Near the probe electrode a thin layer, called plasma sheath, which has a Debye-length thickness forms out as a boundary to the normally undisturbed plasma. Within this layer, the electron- and ion number densities differ according to the applied probe potentials. The influence of a probe electrode on the plasma depends strongly on the probe dimensions and the properties of the undisturbed plasma. The applicable-probe theory has to be choosen with respect to the Debye-length λ_D, the mean free paths of the plasma particels λ_{ei} and the probe radius r. By relating these parameters, six regimes of probe operations, divided into two domains with respect to the Knudsen-number are defined, differing in collisionless or collisonal descriptions of particles movements in the plasma sheaths of different thickness with respect to the probe radius [12]. For plasmas in which the thickness of the sheath, given by the Debye length is smaller than the mean free path of the charged particles, the particle movement can be asssumed collisionless ($\lambda >> \lambda_D$), however, the movement of the particles within the sheath can become complex by orbital motions in a sheath thicker than the probe radius.

1.	$Kn = \lambda_{ei}/r >> 1$	Classical Langmuir theory
1.1	$\lambda >> r >> \lambda_D$	conventional thin sheath
1.2	$\lambda >> \lambda_D >> r$	thick sheath, orbital motions
1.3	$\lambda_D >> \lambda >> r$	collisional thick sheath
2.	$Kn = \lambda_{ei}/r << 1$	Continuum thoery
2.1	$r >> \lambda_D >> \lambda$	collisional thin sheath
2.2	$\lambda_D >> r >> \lambda$	collisional thick sheath
2.3	$r >> \lambda >> \lambda_D$	collisionsless thin sheath, dense plasmas

Table 1: Regimes of electrostatic probe operations.

In the case of small Knudsen numbers Kn<<1, the probe is always collisional relative to the gas particles, but within the sheath, the particle movement may be collisional or collisionless.

To apply the correct probe theory, an estimation of the properties of the investigated plasmas must be performed. The estimation is normally based on numerical models or parameters evaluated by other diagnostical means. The charged particle densities in the regions of the Argon- (Ar), Nitrogen- (N_2), Nitrogen/Oxygen- (N_2/O_2) and simulated decomposed Hydrazine-(N_2+2H_2) plasma jets [13] investigated with electrostatic probes, are in the range of $n_o = 10^{17}$ to 10^{20} m^{-3}. With electron temperatures T_e of 1000 to 30000 K, this results in Debye-lengths of $\lambda_D < 40\,\mu m$. The Coulomb mean free paths are in the range of $\lambda_{ei} \geq 1$ mm and therefore the plasma sheath can be assumed collisionless ($\lambda >> \lambda_D$) [14].

These estimations are based on the assumption of only single ionized particles and the quasi-neutrality $n_i = n_e$ of the investigated plasmas. The directed plasma velocities v are up to 5000 m/s for thermal arcjets plasmas [1] and plasmas generated by MPG expanding against high

ambient pressures of up to 2000 Pa [15]. The directed velocity of an MPD plasma could reach values of about v = 15000 m/s, depending on the power level. With these high directed velocities, ratios of $R_v = v_i/v_{th} = 1 - 6$ are calculated. This calculation is also based on the mass m_i of singly ionized species. Most nitrogen -plasmas are full dissociated, therefore the plasma parameters are calculated using the atomic mass of nitrogen.

It has been experimentally verified [17] that the collisionless theory of Lamframboise [18] for cylindrical probes is valid, if the probe is aligned with the plasma stream in a flowing plasmas and if the probe is long enough to ensure "End effect" parameters [19] of $\tau_l >= 50$. Laframboise has calculated the ion and electron current collection for spherical and cylindrical probes of Maxwellian plasmas over a wide range of Debye-ratios r/λ_D, temperature ratios T_i/T_e and normalized probe potentials χ_p. Within the investigated plasmas the electron temperature T_e is larger than the ion temperature T_i by a factor of 2-3.

Single-probes

Electrostatic single-probes, also known as classical Langmuir probes [9], are most commonly used for plasma diagnostics. The probe consists of a small cylindrical probe inserted into a plasma stream, connected to a power supply by which the probe can be biased at various positive and negative potentials with respect to the plasma. The current I to a probe is measured as a function of the applied voltage. For large negative probe potentials V, all electrons are rejected by the probe, only ions are drawn resulting in an ion saturation current. For less negative probe potentials in the electron retarding region of the probe characteristic, an increasing amount of electrons contributes to the net current drawn by the probe while the ion current part decreases. At the floating potential V_F no net current is drawn since the ion current I_i equals the electron current I_e. At probe potential positive with respect to the plasma potential V_{PL}, the ions are rejected and only electrons contribute to the probe current. The values of the electron saturation current are much higher than of the ion saturation current due to the higher thermal motion of the electrons.

For a Maxwellian, quasineutral, flowing plasma, the electron current density at any potential V with respect to the plasma potential is given by [12]:

$$j_e = j_{eo} \exp\left(\frac{eV}{k T_e}\right). \qquad (1)$$

Here j_{eo} is the electron current density at the plasma potential with V=0 and given by:

$$j_{eo} = e n_{eo} \sqrt{\frac{kT_e}{2\pi m_i}}. \qquad (2)$$

Taking the logarithm of Eq. 1 yields

$$\ln j_e = \ln j_{eo} + \frac{eV}{kT_e} \qquad (3)$$

and by differentiating one obtains the formula:

$$\frac{d \ln (j_e/j_{eo})}{dV} = \frac{e}{kT_e}. \qquad (4)$$

If the electron energy distribution function is Maxwellian, the electron temperature T_e can be obtained by plotting the slope of the logarithmic electron current in the retarding region versus the probe potential. This is only applicable if the electron diffusion current to the probe is not altered by electron-neutral collisions. Since the neutral mean free paths λ_f are larger than the electron mean free paths λ_{ee}, this can be neglected. By the theory of Laframboise [18], the ion current density to a single-probe aligned with the plasma is given by

$$j_i = e n_e \sqrt{\frac{kT_e}{2\pi m_i}}\, i_i\left(\chi_p, \frac{T_i}{T_e}, \frac{r}{\lambda_D}\right). \qquad (5)$$

The correction factor i_i depends on the normalized plasma potential χ_p, the Debye-ratio r/λ_D and the temperature ratio T_e/T_i. The correction factor can be set to 1 in good approximation if the Debye-ratio is greater than 50, which can be obtained by choosing the corresponding probe radius r in accordance with this requirement and if the ion current is obtained by the extrapolation of the saturation current region to values of small normalized probe potentials χ_p [12,18].].

The plasma potential V_{PI} can be obtained by the shape of the logarithmic electron current to a single-probe. The plasma potential is given by the crossing point of the extrapolated linear electron retarding region and the saturation region of the $\ln(I_e)$ [11]. The shape of the second derivative of the electron current I_e to a single-probe with respect to the probe potential $V - V_{PL}$ is proportional to the shape of the energy distribution function of the electrons which can be numerically fitted [12]. To do this, the plasma potential must be exactly known since the probe potential must be measured with respect to the plasma potential.

Double-probes

Electrostatic double-probes [20] are usually two electrodes of equal areas, that come in contact with the plasma. The

electrodes are separated by a distance larger than the plasma sheath thickness λ_D in order not to disturb each other. The double-probe circuit is an isolated closed floating circuit, with both electrodes always negative with respect to the plasma. By applying a voltage difference V between the two electrodes, the more negative electrode draws ion current. Since one of the two electrodes is always more negative, only the ion saturation current region can be reached. Only high energy electrons penetrating the plasma sheath near the floating potential V_F, contribute to the net current. This applies also to double-probes but the electron temperature T_e is obtained by the equation:

$$\left.\frac{dI}{dV}\right|_{V=0} = \frac{I_{i1} I_{i2}}{I_{i1}+I_{i2}} \frac{e}{kT_e} . \qquad (6)$$

The ion currents I_{i1} and I_{i2} are extrapolated from the saturation regions of the characteristic to the floating potential V_{PL} where no current is drawn. The major advantage of the double-probe isthat it is less sensitiv to deviations of the Maxwell electron energy distribution [10-12].

Triple-Probes

The disadvantange of single and double-probes are large heat loads during the positioning of the probes in the plasma jet to obtain the probe characteristics. Also the current to the probe may result in high thermal loads, leading to extensive erosions in chemically reacting plasmas like nitrogen-oxygen. With an electrostatic triple-probe [21], the whole radial distribution of the electron temperature and the electron density can be measured by a fast radial motion of the probe through the investigated plasma jet. No further evaluation of characteristics taken at specific radial test positions is necessary.

The electrostatic triple-probe consists of three symmetrical electrodes of surface area A, two of them (1,3) connected as a double-probe and a third (2) floating with respect to the plasma. In a collisionless thin sheath plasma, the current to each electrode can be expresssed by:

$$\begin{aligned} -I_1 &= A\, j_i(V_1) - A\, j_e \exp(-eV_1/kT_e) \\ I_2 &= A\, j_i(V_2) - A\, j_e \exp(-eV_2/kT_e) \\ I_3 &= A\, j_i(V_3) - A\, j_e \exp(-eV_3/kT_e) \end{aligned} \qquad (7)$$

For further discussion the potential differences $V_{d2} = V_2 - V_1$ and $V_{d3} = V_3 - V_1$ are introduced. Without an externally applied potential difference V_{d2} the current I_2 will be zero and by assuming no variation in ion current density j_i in the probe region one obtains the current ratio:

$$\frac{I_1+I_2}{I_1+I_3} = \frac{1}{2} = \frac{1-\exp(-eV_{d2}/kT_e)}{1-\exp(-eV_{d3}/kT_e)} . \qquad (8)$$

Resolving the equation for V_{d2} yields:

$$V_{d2} = \frac{kT_e}{e}\left[\ln 2 - \ln(1+\exp(-eV_{d3}/kT_e))\right] . \qquad (9)$$

For an externally applied fixed potential difference V_{d3} in the double-probe circuit, an electron temperature dependent potential voltage difference V_{d2} can be measured between the double-probe and the floating electrode. For high values of V_{d3}, reasonable values of electron-temperature T_e can be directly obtained in a linear dependence on the measured value of V_{d2}. By moving the probe through the plasma, direct radial and axial distribution of T_e can be measured. From the collisionless probe theory and the measured current I in the double-probe circuit, the electron number density is determined by:

$$n_e = \frac{\sqrt{m_i}\, I}{A} \frac{\sqrt{e}}{e\sqrt{kT_e}\left[\exp(-eV_{d2}/kT_e)-1\right]} . \qquad (10)$$

Since the ion current density j_i depends on the electrode potentials, the assumption of equal ion current densities is not quite correct even for the thin sheath case. Therefore Chen and Sekiguchi derived an approximate expression for the ion current density which includes a correction factor β. This correction factor scales the potential difference with respect to the floating-potential V_F. With $\Delta V = V_F - V$, the expression is given by:

$$\left[I_i(V)\right]^2 = \left[I_i(V_F)\right]^2 (1-\beta\Delta V) . \qquad (11)$$

Using this expression within the current ratio of the direct display system with the floating single-probe, one obtains:

$$\frac{1}{2} = \frac{1-\left((1-\beta V_{d2})^{1/2} + (1+\beta(V_{d3}-V_{d2}))^{1/2}\right)}{1-\exp(-eV_{d3}/kT_e)} \qquad (12)$$

$$0.5 \exp(-eV_{d2}/kT_e)$$

to determine the electron temperature. The equation for the electron density changes to:

$$n_e = \frac{\sqrt{m_i}\, I}{A} \frac{1.05\cdot 10^9 \left(1-\beta(V_F - e/2KT_e)\right)^{1/2}}{\sqrt{T_e}\left(\exp(eV_{d2}/kT_e) - (1-\beta V_{d2})^{1/2}\right)} \qquad (13).$$

In the case of $\beta = 0$, the corrected expression for the electron temperature and the electron density reduce to Eq. 9 and 10 [21]. The exact value for the correction factor β can be obtained by single-probe characteristic of a triple-probe electrode [21]. Recent work on triple-probes [22] was focused on applying a more accurate correction using the Peterson-Talbot [23] curve fits on the Laframboises theory of current collection which applies also to triple-probes. The improvement by this method is significant for low values of the Debye-ratio r/λ_D.

Time of Flight probes

Time of flight probes [24] are electrostatic probes separated at a known distance and aligned with the flow of the plasma particles. Double-probes are most convenient for time of flight probes because while floating with the plasma potential, they are not affected by fluctuations of the plasma potential between widely separated electrodes like in the single-probe case. Upstream and downstream probes are both biased to draw ion-saturation current. Fluctuations in the local ion number density around a probe result in fluctuations in the detected ion current. By moving with the flow velocity v those fluctuations are first detected at the upstream probe and then time delayed at the downstream probe. The method of time of flight probes as described is only applicable within free-stream conditions because a relatively large probe separation of about 25 - 50 mm is needed to resolve the durations of time delays in high speed plasmas. By performing a FFT-cross-correlation with the two signals, the exact value of the time shift respectively the time of flight can be is easily determined. With the known separation of the two probes, the velocity of the plasma particles can be calculated.

Crossed single-probes

Theoretically formulated [25] and experimentally verified [26-28], the ion current to a cylindrical probe in a plasma flow depends strongly on the angle θ between the probe axis and the plasma flow vector. For a probe electrode not aligned with the plasma flow, the kinetic energy of charged particles moving towards the electrode results in a deformation of the potential sheath around the electrode in which the charged particles are sampled and contribute to the probe current. For electrodes aligned with the plasma flow vector, only those charged particles which enter the potential sheat by random thermal motion like in stationary plasmas contribute to the probe current. In general the ion current to a probe at an angle θ with respect to the velocity vector can be described by the following equation [25]:

$$I_i = \sqrt{\frac{kT_e}{2\pi m_i}}\, n_e\, e\, A \frac{2}{\sqrt{\pi}} \exp\left(-(v_i/v_{th})^2 \sin^2\theta\right) * \sum_{n=0}^{\infty} \left(\frac{(v_i/v_{th})^n \sin^n\theta}{n!}\right)^2 \Gamma\left(n+\frac{3}{2}\right) \quad (14)$$

Here v_i is the directed ion flow velocity, A the probe surface area and v_{th} the thermal velocity given by:

$$v_{th} = \sqrt{\frac{2kT_i}{m_i}}. \quad (15)$$

For two single-probes, with one orientated perpendicular ($\sin\theta = 1$) and one aligned with the flow vector, see Eq. 5, the ratio of the two currents becomes:

$$\frac{I_{i\perp}}{I_{i\parallel}} = \frac{2}{\sqrt{\pi}} \exp\left(-(v_i/v_{th})^2\right) \sum_{n=0}^{\infty} \left(\frac{(v_i/v_{th})^n}{n!}\right)^2 \Gamma\left(n+\frac{3}{2}\right) \quad (16)$$

Fig. 1. shows the values of the ratio of directed and thermal velocity $R_v = v_i/v_{th}$ versus the current ratio for probes of equal surface area in plasmas of lower directed velocities. If the ion temperature and therefore the degree of thermal nonequilibrium T_e/T_i ist known, the directed ion velocity v_i can be derived from the velocity ratio. Otherwise the method for ion temperature determination is as follows. By using two crossed single-probes, the current ratio and therefore the velocity ratio can be detected. By knowing the directed velocity of the plasma from time of flight measurements, the ion temperature T_i can be calculated by the equation:

$$T_i = \frac{v_i^2 m_i}{2kR_v^2}. \quad (17)$$

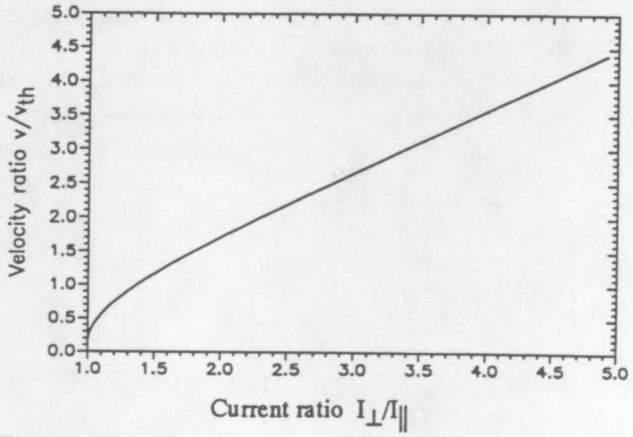

Figure 1: Velocity ratio versus current ratio.

There are some crucial assumptions underlying the crossed probe methods. To obtain the correct current ratio the surface area of both probes must be known or assumed to be equal. Especially in chemically reacting plasmas a high erosion rate of the perpendicular electrode is observed, which has to be taken into account. Within supersonic flows like in MPD plasmas, the effective area of the perpendicular probe changes due to wake effects on the back side. A correction factor of 2 for the current to the perpendicular probe can approximately applied [26]. Since the method of measuring the ion temperature is a combination of two independend methods, the errors are at about ±50 % of the absolute value for the ion temperture T_i and at about 20 % for the ion velocity v_i [8].

Rotating single-probes

The dependence of the ion current on the angle of attack θ as described by Eq. 14, can also be used for the determination of the plasma flow. If a single-probe which rotates in the plasma flow is aligned with the plasma streamlines (θ = 0°), the current to the probe must show a minimum according to sin θ = 0. The line shape of the ion current to the single-probe versus the angle of attack gives the angle of alignment and therefore the plasma flow, most commonly with respect to the plasma jet axis. Several authors mentioned a sharp increase in the ion current at small angles around alignment of the probe with the plasma flow [19]. This current peak is governed by the so called "End -Effect" parameter which is given by:

$$\tau_l = \frac{l}{\lambda_D} \frac{\sqrt{kT_e / m_i}}{v_i} . \qquad (18)$$

with l as the probe length. For the investigated plasma conditions, this "End-Effect" parameter can be set to values of $\tau_l > 50$ for which the "End-effect" can be neglected [12,19], by using probe electrodes of corresponding lenght l. Normally electrodes of l = 10 mm are convienient in order to neglect "End-Effects".

Fixed angle-probes

The plasma flow determination at positions very close to the thrusters or plasma sources cannot be performed by rotating single-probes due to the high heat loads on the probes. Therefore a new probe method to detect plasma streamlines has been developed. This probe method is also based on the dependence of the ion current on the angle of attack θ to the probe.

An electrostatic single-probe is mounted at a fixed angle α_s with respect to the plasma jet axis. By biasing the probe to draw ion current and moving it radially through a diverging plasma jet, the probe will reach a position y at which it is aligned with the plasma flow. Since the governing parameters on the ion current, n_e and T_e are normally also changing rapidly with the radial position y, a current minimum at the position of alignment cannot be identified. The radial change of the parameters n_e and T_e can be detected by a probe which is aproximately unaffected by the angle of attack θ. For this purpose, a plane single-probe electrode is used. The ratio of the ion current to the probe at a fixed angle and the current to the plane probe shows a minimum at the position of alignment. This method was verified by a theoretical model of a plasma jet including radial distributions of electron temperature $T_e(y)$, electron density $n_e(y)$, plasma velocity $v_i(y)$ and plasma flow angles $\delta_p(y)$ with respect to the plasma jet axis. For a simulated probe at fixed angel α_s, the angle of attack is calculated to

$$\theta(y) = \delta_p(y) - \alpha_s . \qquad (19)$$

With this set of parameters the ratio of ion current to the probe at a fixed angle was calculated by Eq. (14), and also the current to a plane probe was obtained by setting θ = 0°. Typical results of the theoretical model for angles $\alpha_s = \pm$ 10° and ±20° are shown in Fig. 2.

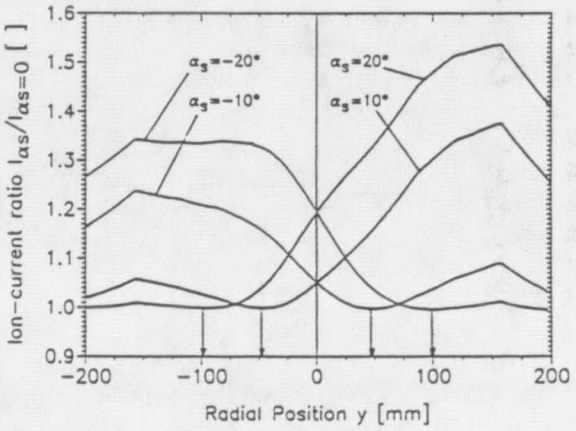

Figure 2: Current ratios $I_{\alpha s}/I_{\alpha s=0°}$.

The current ratio minima are exactly at the positions y of the corresponding model angles $\delta_p(y)$.

Experimental performance of measurements

In Fig 3. the cross section of a typical triple-probe head is shown. The three electrodes of the probe are made of tungsten wires of typically 0.4 mm diameter but the diameter 2r can be varied between 0.1 to 1 mm, the length l is in the range of 10 to 20 mm. The isolation of the electrodes is made of alumina tubes of different diameters depending on the diameters of the electrodes. The electrodes respectively the alumina tubes are mounted in a

row in a cylindrical probe head made of brass. The connection to the data acquisation is performed by heat resistant and isolated cooper wires which are pinched to the electrodes. The construction for single- and double-probes differs only in the number of electrodes. For crossed single-probes or fixed angle-probes, the tungsten wires outside of the isolator are bend to the required angle and direction. The complete probe head can be mounted to one of two possible positions of the probe support shown in Fig. 4.

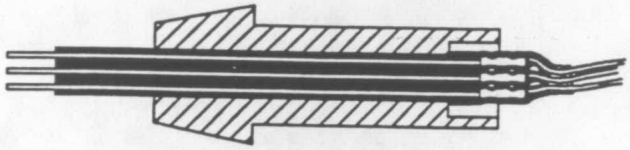

Figure 3: Triple-probe construction

The probe support is a water cooled brass construction. It offers the possibility of four BNC-connections for probe wires. Therefore two double-probes or a single- and a triple-probe can be operated by rotating the probe support for an angle of 180°. The probe support is mounted to the x-y-z platform in the PWK which allows also the rotation of the probe support around the z-axis or on the single axis motion system of the thruster tanks. For the determination of plasma streamlines, the probe support was constructed in such a way that the center of a single-probe electrode is positioned exactly at the rotational axis.

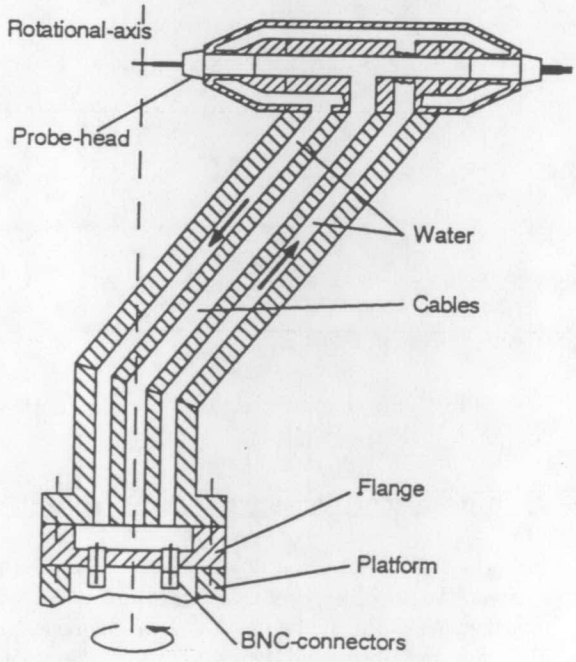

Figure 4: Probe support.

For the investigation of an 1.5 kW arcjet thruster, electrostatic probes are mounted on a pendulum mechanism which can be swung through the plasma plume with different speeds and at different axial positions x.

Fig. 5 shows the experimental setup of the triple-probe. The fixed voltage of the double-probe circuit ist applied by an external, IRS-built power supply of ±30 V. The double-probe current is measured as potential drop over a 10Ω shunt of 1% accuracy. A transient recorder with a high input impedance of 1MΩ, which is necessary to measure reliable values of the floating potential V_{d2} [23], was used for data acqusition. The same setup is used for single and double-probe measurements, but the probe potential is then modulated in a sinusoidal form with frequencies of up to 1 kHz in order to acquire current-voltage characteristics. For experiments with the fixed angle-probes, the currents to the electrodes are measured by several shunts like in the double-probe curcuit of the triple-probe. This applies also to the current measurement of a rotating single-probe. For time of flight measurements, the double-probes, mounted at a certain distance to each other, are oriented perpendicular to the plasma flow.

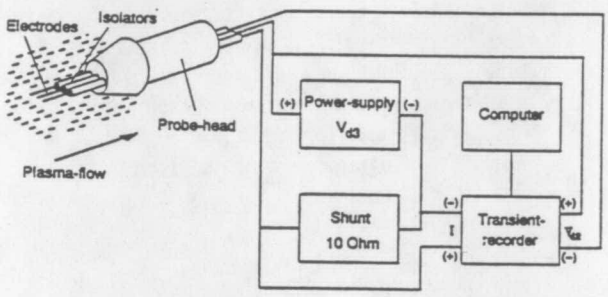

Figure 5: Triple-probe measurement set-up.

The obtained probe data is evaluated by specific programmes.

Experimental results

Since the alignment of the cylindrical probes with the plasma flow is essential in order to obtain correct values of the plasma parameters by the theory of Laframboise, results of the plasma streamlines are discussed first. In Fig. 6 the streamlines of an MPG nitrogen-plasma flow at low ambient pressures are shown.

The solid lines represent the flow measured with rotating single-probes, the dotted lines are streamlines measured with fixed angle-probes. The plasma flow expands up to an axial distance of about x = 325 mm. At that distance the plasma flow converges.

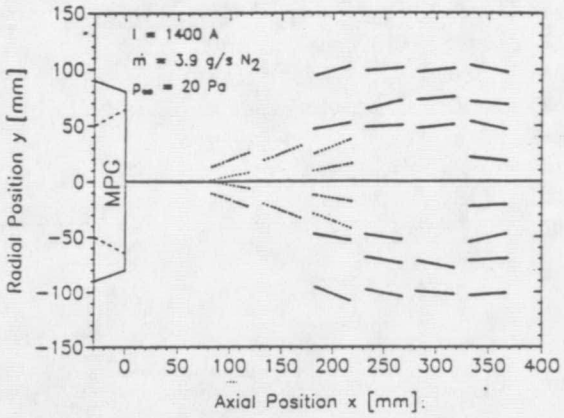

Figure 6: Plasma streamlines measured with rotating single- and fixed angle-probes.

The data of the nitrogen plasma flow in the PWK at low ambient pressures compares well with the flow of an MPD Argon-plasma at a current level of I = 2000 A and a massflow rates of m = 0.8 g/s Argon. The $\delta p = 20°$ streamline was measured at an axial distance of x = 300 mm at y = -50 mm and +60 mm [29]. The radial position of the $\delta_p = 20°$ streamline in the nitrogen plasma increases with increasing axial distance to the MPG. At x = 150 mm it is detected at y ≈ -21 mm and +28 mm as shown in Fig. 7.

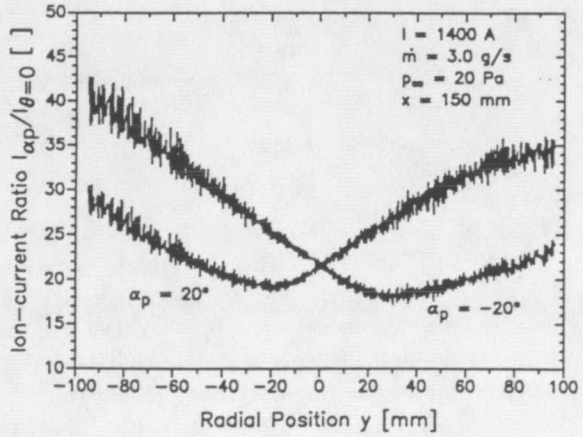

Figure 7: Current ratios of a fixed angle-probe.

At ambient pressures above 100 Pa, the plasma jet can be assumed to be nearly parallel. The small diverging angle of $\delta_p = 4.9°$, measured from the half width of radial ion current distributions at different axial positions and shown in Fig. 8, does not significantly alter the probe response provided that "End-Effects" can be neglected by large values of τ_I. This can be calculated from Eq. 14. by varying the angle θ.

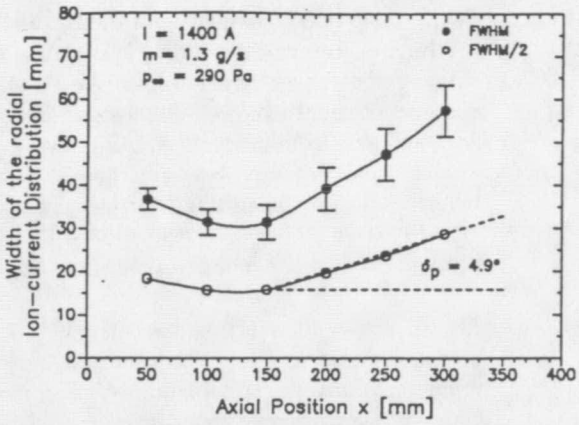

Figure 8: Half-width of radial ion-current profiles to a triple-probe at an ambient pressure of 290 Pa.

Electron temperatures T_e obtained with single-, double- and triple-probes in a parallel nitrogen plasma flow are shown in Fig 9. The corresponding electron densities are shown in Fig. 10.

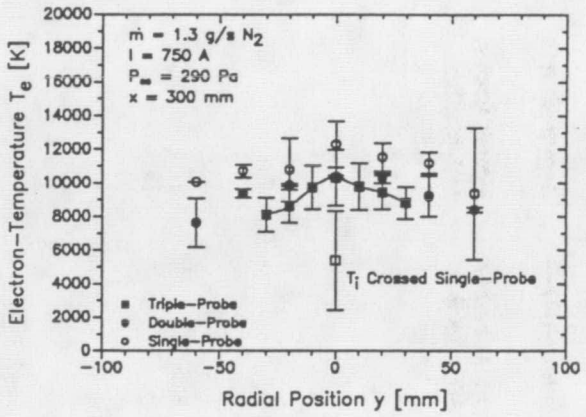

Figure 9: Electron temperatures in a MPG-nitrogen plasma flow.

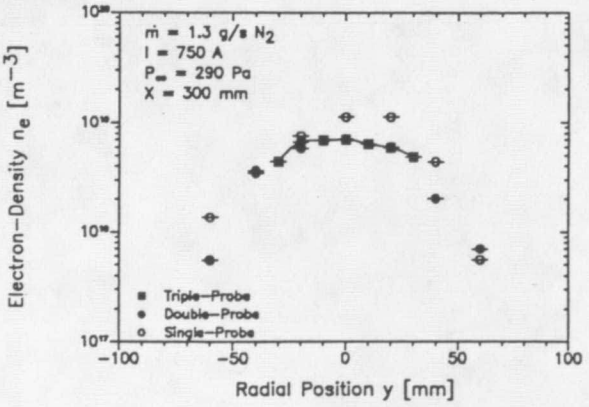

Figure 10. Electron densities in a MPG-nitrogen plasma flow.

While the values obtained with double and triple-probes are in good agreement within 12% relative deviation, the single-probe shows higher values. An examination of the electron current shows deviations of the assumed Maxwellian electron energies. As floating systems, the double- and triple-probes are not affected. The ion temperature in the plasma centerline, measured with crossed single-probes in combination with a time of flight probe gives an thermal nonequilibrium of $T_e/T_i \approx 2$.

Fig. 11 shows the electron temperature in the Hydrazine plume of an 1.5 kW arcjet thruster measured with double-probes. The electron temperature was also measured by an emission spectroscopic investigation of the H_α and H_β Balmer lines [13]. With both methods, comparable results were obtained, thus they verify each other.

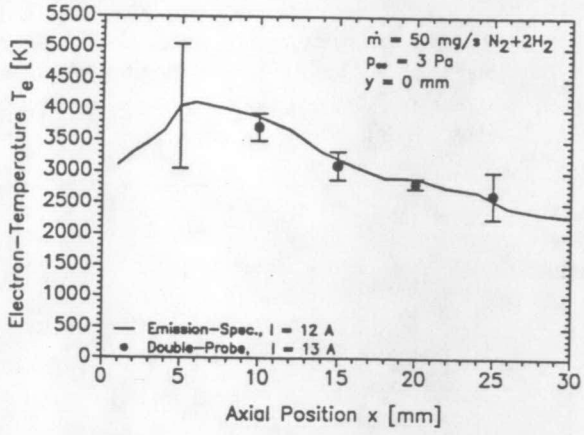

Figure 11: Axial electron temperatures in a Hydrazine arcjet plasma.

In an expanding MPD plasma, the electron temperature and electron density was measured with double and triple-probes. This is shown in Fig. 12 to 14.

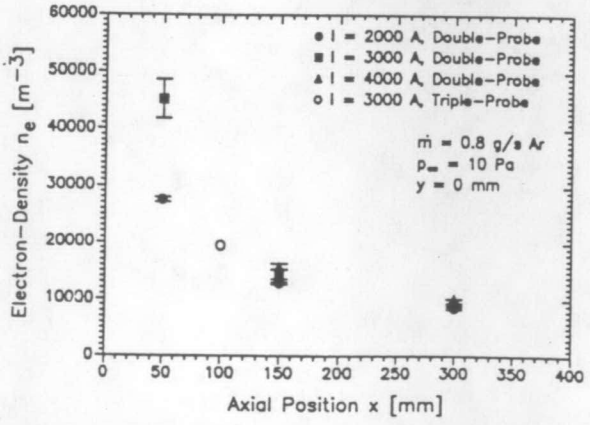

Figure 12: Axial electron temperature in an MPD-Argon plasma.

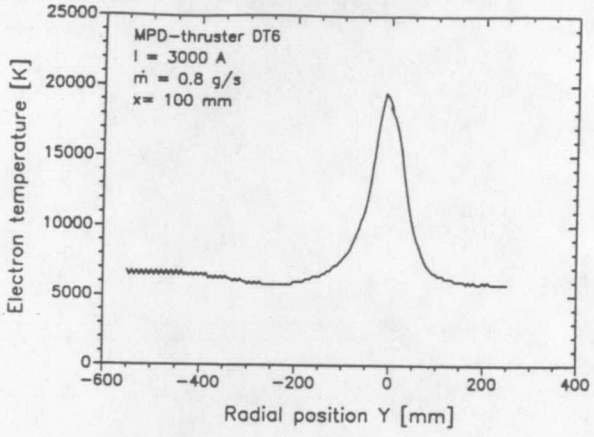

Figure 13: Radial electron temperature distribution measured with a triple-probe.

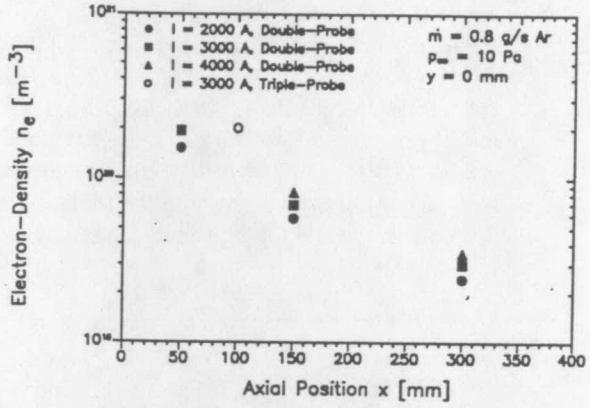

Figure 14: Axial electron densities in an MPD-Argon plasma.

The centerline values of the triple-probe at an axial distance of x = 100 mm compares very well to the extrapolated axial double-probe values. Refering to Fig. 6, the triple-probes were approximately aligned with the plasma flow by mounting them at fixed angles of $\alpha_s = \pm 10°$ for the corresponding side of the coordinate system.

The radial profiles of the ion velocities at two axial positions in a MPG-nitrogen plasma flow are shown in Fig. 15. With this velocity profiles, the total pressure in the plasma jet was calculated using the Bernoulli equation for compressible flows [29]. This method is very sensitive to inaccuracies in the velocity used for the calculation, and so far the comparison of the calculated total pressure to the total pressure measured with a Pitot-probe gives a very good verification of the time of fligth method as shown in Fig. 16.

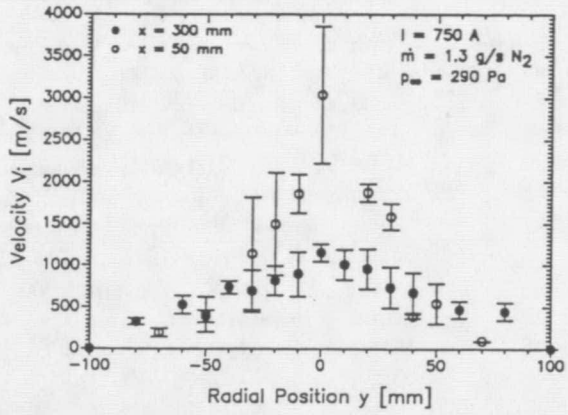

Figure 15: Radial ion velocities.

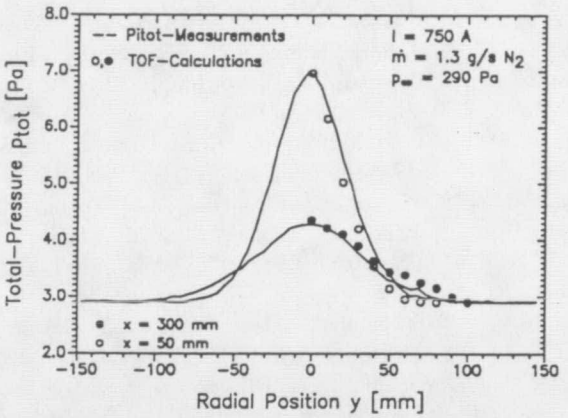

Figure 16: Comparison of measured total pressures and pressure-calculations based on velocity measurements.

Convienient natural fluctuations of the ion current density were only observed in plasmas of high massflow rates and high ambient pressures. The application of the time of flight method to MPD-thruster plumes is very difficult and most commonly limited to pulsed or quasistationary thrusters. If the ion temperature is known, the ion velocity can be measured with crossed single-probes, see Fig. 17.

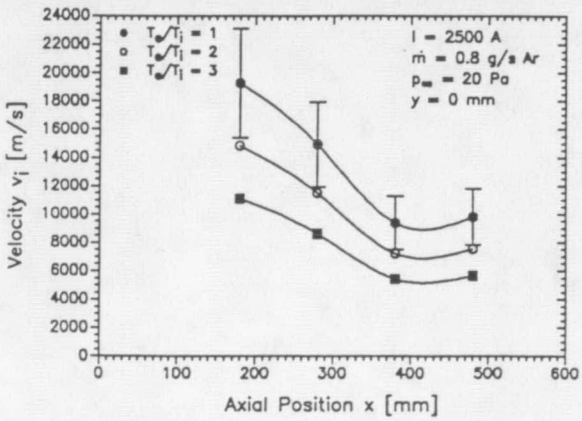

Figure 17. Axial ion velocities measured with crossed single-probes in a MPD Argon-plasma.

Conclusions

The presented electrostatic probe methods are now all available at the IRS for investigations of arc-generated flowing and collisionless plasmas. The different probe methods show reasonable agreements within 20% of the measured values of electron temperatures and densities. The time of flight probes are fully qualified and verified by several independent means for application im MPG-plasmas. The detection of plasma streamlines is now possible at position close to the plasma source. The next step for the work on electrostatic probes will be the exact determination of the electron energy distribution functions and the examination of the triple-probe response to plasmas with large gradients of the ion current density over the probe dimension.

Acknowledgements

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