High Precision Beam Diagnostics for Ion Thrusters

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Benjamin van Reijen[1], Norbert Koch[2], Alexey Lazurenko[3], Stefan Weis[4], Martin Schirra[5], Angelo Genovese[6], Jens Haderspeck[7]
Thales Electron Devices GmbH, Söflingerstr. 100, 89075 Ulm, Germany

Eberhard Gill[8]
Delft University of Technology, Kluyverweg 1, 2629HS Delft, The Netherlands

Abstract: The Thales diagnostic equipment for ion beam characterization consists of a gridded and single orifice retarding potential analyzer (RPA) and an energy selective mass spectrometer (ESMS). During the development phase of these sensors considerable effort was put into the removal of ion optical effects as well as to ensure equal ion transmission ratios for low and high energetic ions for both devices. To this end simulation software was used to look into the trajectories of ions from a wide range of potential energy, angle of incidence and charge state. The simulations verified effects due to RPA grid misalignment and were the foundation for the development of a single orifice RPA and the adaptation of the ESMS. Experimental testing verified the improved performance of the sensory equipment due to ion trajectory simulation.

Nomenclature

RPA	=	retarding potential analyzer
ESMS	=	energy selective mass spectrometer
HEMP-T	=	high efficiency multistage plasma thruster
ERE	=	electron repelling electrode
IRE	=	ion repelling electrode
SEE	=	secondary electron emission repelling electrode

[1] Electric Propulsion Development Engineer, Plasma Devices, benjamin.reijen@thalesgroup.com; corresponding author
[2] Head of Plasma Devices, Plasma Devices, norbert.koch@thalesgroup.com.
[3] Manager Electric Propulsion Testing, Plasma Devices, alexey.lazurenko@thalesgroup.com.
[4] Electric Propulsion System Manager, Plasma Devices, stefan.weis@thalesgroup.com.
[5] Manager Electric Propulsion Component Development, Plasma Devices, martin.schirra@thalesgroup.com.
[6] Electric Propulsion Testing Engineer, Plasma Devices, angelo.genovese@thalesgroup.com.
[7] Electric Propulsion System Engineer, Plasma Devices, jens.haderspeck@thalesgroup.com.
[8] Chair of Space Systems Engineering, Department of Space Engineering, E.K.A.Gill@tudelft.nl.

I. Introduction

Ion beam diagnostics are vital tools for electric propulsion development programs to increase understanding of the thruster physics as well as to quantify the thruster-spacecraft interaction such as ion beam impingement and to validate qualification parameters such as the thrust vector[1]. For both beam impingement calculations and thrust vector verification an angle resolved analysis of the ions must be performed. The required properties to be measured are the ion current density, the ion potential and the ion energy specific charge state, as can be seen in eq.(1) where the thrust T is a function of the massflow $\dot{m}$, the mean origin potential of the ions U_{pot}, the charge state q multiplied with the elementary charge e, and the molecular mass M of the propellant.

$$T = \dot{m}\sqrt{\frac{2U_{pot} \cdot q \cdot e}{M}} \tag{1}$$

Within the qualification project of the HEMP-T electric propulsion system[2,3], beam diagnostic equipment was developed for precise measurements on the beam profile with regard to the required ion properties. The developed equipment consists of two retarding potential analyzers (RPA), one gridded[4], one with a single orifice, and an energy selective mass spectrometer (ESMS), which was adapted to ion beam measurements. Although these types of sensory equipment are well documented and widely applied[4,5] their design is not straightforward with respect to their accuracy of low and high energetic ion transmission. The accurate representation of the ion potential spectrum depends highly on the ion optical characteristics of the devices. The development of these sensors at Thales was founded on ion trajectory simulation to investigate the response of the sensors based on ions with a wide range of potential energy, charge states and angles of incidence.

II. RPA and ESMS basics

A RPA is an electrostatic device that uses an electric field to repel ions that enter the device[1]. Ions of higher potential than that of the electric field pass through and are detected; the sensor current is a function of the applied potential to the repelling electrode. The resulting ion energy spectrum current density φ follows from the negative differential of the sensor signal I_{RPA} to the applied retarding field U_{pass}, divided by the orifice surface A_{coll} and the elementary charge e, as seen in eq.(2) and figure 1.

$$\varphi = -\frac{dI_{RPA}}{dU_{pass}} \cdot \frac{1}{A_{coll} \cdot e} \tag{2}$$

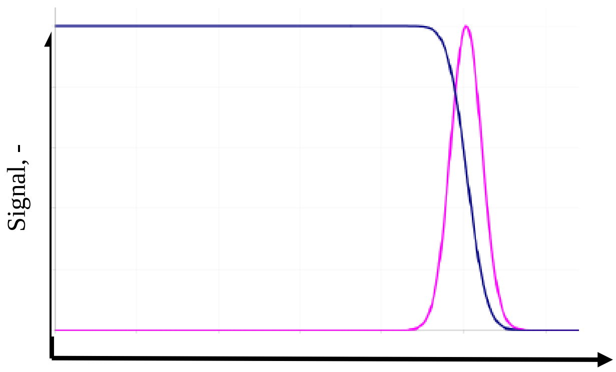

Figure 1. RPA raw signal (blue) versus resulting energy spectrum (pink) of a gauss curve around 1kV

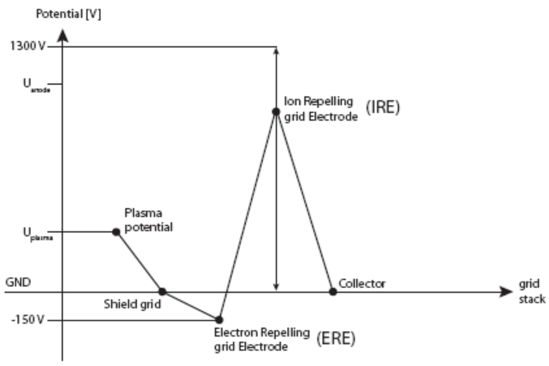

Figure 2. Qualitative representation of the electrode potentials and their position in a RPA electrode stack

The basic design upon which the Thales RPAs are based is an electrode stack which successively provides a grounded reference entry electrode, a negatively charged electron repelling electrode (ERE) to repel and remove the electrons from the ion beam, a positively charged ion repelling electrode (IRE) and a sensor surface which detects the current needed to neutralise the positive ion flux upon its surface, see figure 2. RPAs can measure the ion current density and the ion potential, but as RPAs are purely electrostatic devices they are incapable of differentiating between single and multiple charged ions from regions of equal acceleration potential.
The detection of the ion charge state can be done by magnetic or high frequency electric fields. To this end Thales acquired a Balzers/Inficon PPM422 quadrupole energy selective mass spectrometer, capable of scanning masses up to 512 amu between -500 and +500 V with an accuracy of ±0.3V, detected by a secondary electron multiplier. Since the HEMP-T anode potential is at 1kV the ESMS is mounted galvanically isolated from the vacuum facility. By this design the ESMS ground potential can be biased, such that the detection of the energy selective charge state of ions up to 2kV is possible. Special designed ion optics guide the ion beam into the entrance optics of the ESMS and ensure equal transmission ratios over the whole ion potential range.
The simulation software CANON OPTIQUE which was used for the ion trajectory simulations is a Thales in-house developed program, originally for electrons in a travelling wave tube, but now adapted for the use with ions as well. The program solves the Maxwell equations for a 2-dimensional finite element space with rotational symmetry and variable mesh size. It also incorporates the effects due to the presence of space charge. The software was the cornerstone for the design of the ESMS and the single orifice RPA, especially with regard to the electrode sizing and assisted greatly in understanding ion optical effects with the gridded RPA.

III. Ion optical effects

Electric fields are to ions what lenses are to light[6,7], see figure 3. The ion optical systems under discussion here are cylindrical electrode devices. The energy and angle of the ion and the sign, magnitude and shape of the electric field lines define whether and to what extent the ion beam is focussed or defocused. When e.g. 800 Volt ions have a focal distance of 20 mm it means that 50 Volt ions have a smaller focal distance and are already diverging again at 20 mm. The difference in focal behaviour of ions from different potential and grid settings is visually clarified in figure 4.

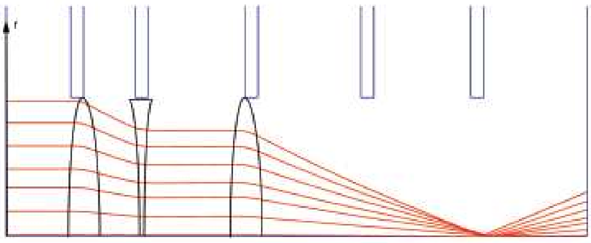

Figure 3. Visual representation how the electrical fields from the electrodes act as lenses to the ions

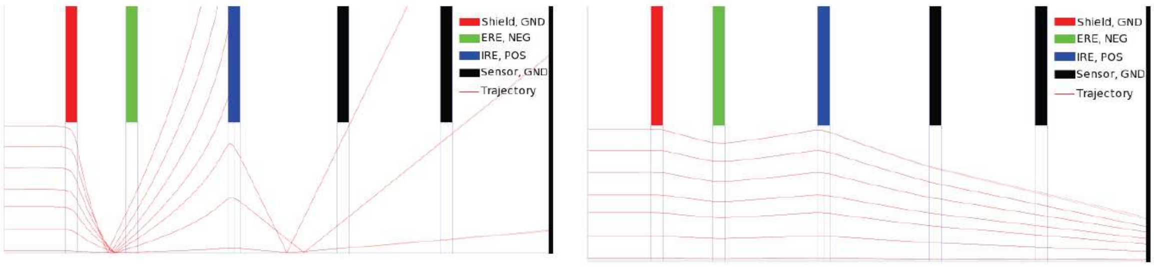

Figure 4. Ion trajectories in a gridded RPA. Focussing behaviour of the ions is heavily dependant upon their mean potential and the applied potential to the grid electrodes.

A difficulty with the RPA is the application of the retarding field: the increase of the potential of the IRE during an energy scan causes a change in the ion optical parameters, changing its focusing behaviour for all ions that have sufficient energy to pass the repelling field. The change in ion optical parameters has different effect on ions of different potentials, two typical behaviours can occur: the change in IRE potential forces ions of higher potentials than that of the IRE to come in contact with electrodes and not the sensor surface (overfocusation), these ions are then ‘detected’ at lower potentials than their true potential. The second case occurs when poorly focused ions (usually of high potential and/or higher angles) experience improved focusation, thus increasing the sensor signal with increasing IRE potential and resulting in a negative representation of the energy spectrum, an obvious physical impossibility.

It is therefore impossible without ion trajectory simulations to ensure the absence of signal losses due to overfocusation or the increase in sensor signal due to improved focussing during the energy scan.
Aside from the topic of focusation, the accuracy of the RPA to measure the actual ion energy spectrum is only as good as its ability to accurately detect the signal strength of ions at each potential level. This requirement is only fulfilled if all ions from all potential levels that pass through the orifice electrode are detected, such that there are equal transmission ratios of ions with energies from one volt to multiple kilovolts, regardless of the potential of the IRE. In the case of gridded RPAs, or in general when all electrode grids are of equal electrode hole diameter, it is imperative that the grids are properly aligned, see figure 5. Slight misalignment severely worsens signal errors present due to ion optical effects.

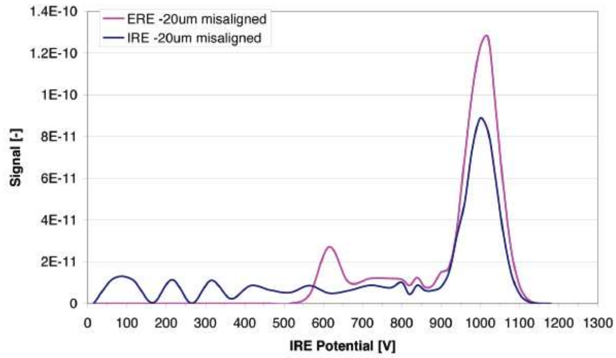

Figure 5. Misinterpretation of the ion potential spectrum due to grid misalignment in a gridded RPA. The original signal is a gauss distribution around 1kV.

IV. RPA and ESMS design

The gridded Thales RPA has 20mm diameter stainless steel grids of thickness 0.2mm with hole diameters 0.3mm arranged in a 60° pattern effecting 40% optical transmission. The grids are welded to an inverted 5 piece top-hat holding structure, protected from the plasma environment by a stainless steel cover[4]. The entrance grid is grounded, followed by the ERE and IRE. The final two grids are short circuited with the sensor cup and do not contribute to the ion optical system.

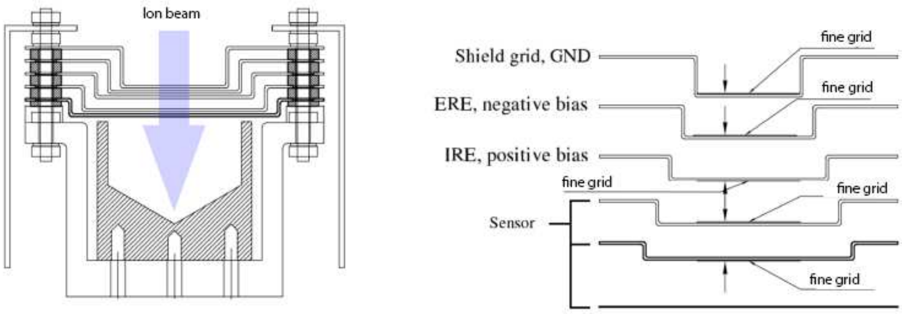

Figure 6. Gridded RPA desing at Thales. Precisely aligned fine grids are welded to a course holding structure.

The single orifice RPA consists of a thick-electrode stack, where the ion optical elements are larger in diameter and longer than the orifice electrode, see figure 7. The entrance electrode is grounded with a 1mm diameter orifice, followed by an ERE, an IRE, a second negative grid and a sensor electrode. The second negative grid acts as a secondary electron emission repeller (SEE) and functions as a focussing electrode in front of the sensor. The increased inner diameters of the ERE, IRE and SEE allow for divergent ion trajectories during the longer drift distance of the thick electrodes.
The ESMS, see figure 8, was originally not designed for ion beam characterization, but can detect ions from -500V to +500V. The HEMP-T anode potential is 1kV, therefore the ESMS and all controllers are galvanically isolated from the facility ground such that their ground potential can be raised up to 2kV. The in-vacuum side of the ESMS is isolated from the plasma environment by a grounded cylinder and the entry cap of the ESMS was replaced by an electrostatic lens system. In this configuration the ESMS is set to the detection of 100V ions while

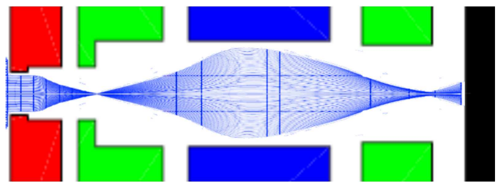

Figure 7. Schematic representation of the Thales single orifice RPA. Axes are not to scale.

its reference potential scans along the energy spectrum, starting from -100V and working its way up. When the ESMS ground is at 900V it will detect the separate charge states of ions around 1kV±0.3V, therefore for each scan step the entry electrode system has to focus only ions of one particular potential level. This is contrary to the RPA where all ions of all potential levels need to be focussed simultaneously. Again the optics system was optimised for equal transmission ratios by identical focussing parameters for low and high energetic ions. The main requirements on the ESMS entry optics is a very narrow parallel beam due to the small acceptance angle of the ESMS energy filter, this also results in a small acceptance angle of the entry optics.

Figure 8. The ESMS mounted to the chamber

V. Test setup

Measurements were taken in the ULAN test facility at Thales in Ulm[7], the thruster under testing was a HEMP-T3050 laboratory model operating at an anode voltage of 1kV. The thruster is mounted at the chamber central axis on a turntable, enabling rotation along the vertical axis of the thruster exit for angle resolved measurements. The sensors are fix mounted: the ESMS is attached to the end cap 3.5 meters from the thruster, the RPAs are mounted off the central axis at a distance of 1 meter. A laser assures alignment of the sensors and provides the measurements for the sensor positions and angles w.r.t. the thruster axis.

VI. Measurement results

When comparing the data from the gridded RPA with the data from the ESMS and the single orifice RPA, see figures 9 and 10, we notice the following differences. The measurement data show a more pronounced low energy tail of the gridded RPA, also its main 1kV peak is smaller in comparison to its low energy peak when compared to the single orifice RPA data. Although special attention was given to the grid alignment this data suggest remaining misalignment from either the ERE or IRE, see fig 5.

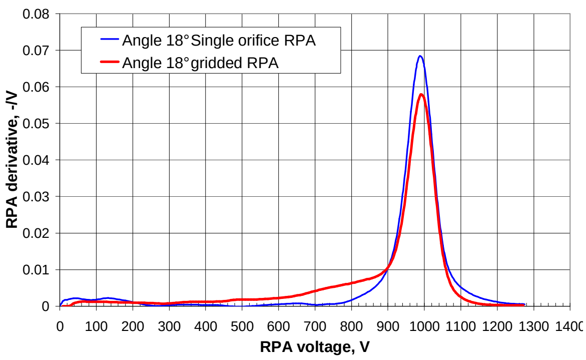

Figure 9. Normalised RPA measured ion potential spectrum of a HEMP-T laboratory model A in floating mode

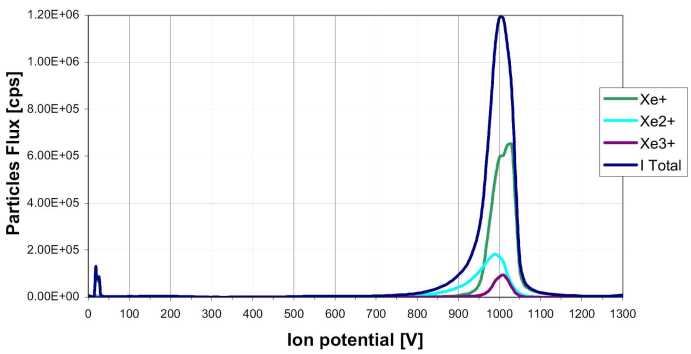

Figure 10. ESMS measurements on a HEMP-T laboratory model B in grounded mode

The ion potential spectrum of the single orifice RPA and the gridded RPA are in good agreement between 50 V and 200 V, below 50 V the gridded RPA suffers losses in ion transmission due to overfocusation. The measurements with the single orifice RPA are comparable to those from the ESMS measurements, qualitively the RPA 1kV peak is slightly broader due to a lower energy resolution of 5V w.r.t. the 0.3V from the ESMS. The single orifice RPA provides sufficient signal to noise ratio and the absence of ion optical effects with excellent repeatability. Both the high and low energy ion peaks are clearly defined and no signal decrease occurs between 250V and 750V.
Figure 10 shows that the ESMS is capable of scanning the entire required ion energy spectrum and successfully provides the energy specific ion charge states for all angles from the ion beam.

A note on the location of the 1kV peak in figures 9 and 10: the RPA data were taken on a thruster in floating mode while the ESMS measurements are of a different model in grounded mode. The difference of the coupling voltage explains the shift in the anode voltage peak.

VII. Conclusion

With the single orifice RPA and the ESMS Thales is capable of high precision beam characterisation for electric propulsion systems. Ion trajectory simulation proved to be a very powerful tool, not only in explaining certain misalignment effects in the gridded RPA, but also as a design tool for accurate RPA design. This is proven by the excellent data from both the ESMS and single orifice RPA. The combination of these two types of sensors enables full beam analysis for impingements effect and thrust level verification.

Acknowledgments

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