Modelling of the Electric Propulsion Induced Plasma Environment on SMART-1

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SMART-1 will be the first spacecraft using a Hall thruster as a primary propulsion system. Part of its mission is to investigate the influence of operating such a thruster with the rest of the spacecraft. Due to collision processes in the plasma, slow ions are produced which are able to leave the primary ion beam. Two instruments in SMART-1 will investigate these slow ions, the Electric Propulsion Diagnostic Package (EPDP) and the Spacecraft Potential, Electron and Dust Experiment (SPEDE). A 3D Particle-In-Cell plasmasimulation has been developed to predict what the instruments will measure and to get estimate the global distribution of these slow ions around the spacecraft. Therefore, virtual instruments were developed to resemble the space experiments as close as possible. Priliminary results show no significant interaction with the rest of the spacecraft and that all obtained data is well within the instrument range.

1. Introduction

SMART-1 is the first of the Small Missions for Advanced Research in Technology of the ESA Horizons 2000 scientific programme. The mission is dedicated to testing of new technologies for preparing future cornerstone missions, using Solar-Electric Propulsion in Deep Space. SMART-1 will be placed in orbit around the moon using a Hall thruster (PPS-1350) with a maximum thrust of 70 mN built by SEP[1]. It will be launched in 2002 as an Ariane 5 cyclade-like auxilary payload.

This will be the first time of primary electric propulsion on a European spacecraft. Hence, the evaluation of the Hall thruster impact on the spacecraft and its instruments is one of the primary scientific objectives[2]. Additionally to primary beam ions, electric propulsion thrusters create a low-energy charge-exchange ion environment. The distribution of these ions is strongly affected by the potential distribution near the spacecraft being a potential contamination source for instruments and solar arrays. Although charge-exchange plasma interactions have been a subject of extensive experimental and theoretical studies[3-5], there have been few comprehensive in-flight investigations due to the lack of flight opportunities. The first interplanetary spacecraft using solar electric propulsion is Deep Space One[5] using the NSTAR ion engine. SMART-1 will be the first interplanetary flight using a Hall thruster.

Two payload experiments (EPDP, SPEDE) are dedicated to measure the ambient plasma variables during the operation of the Hall thruster. The Austrian Research Centers Seibersdorf (ARCS) are currently developing modelling tools to predict and help to interpret instrument data to study spacecraft/environment interactions on SMART-1. This paper will present an overview of the plasma diagnostics and preliminary modelling results of the induced electric propulsion plasma environment to assess possible contamination issues. A successful validation of the simulation with in-flight data will support future interplanetary and commercial missions featuring electric propulsion to reduce the risk of contamination and interference with on board instruments.

2. Spacecraft Plasma Sensors Overview

SMART-1 is a cube spacecraft with the dimensions 1.15x1.15x1 m and two solar arrays stretching out from two opposite sides giving a total length of 8 m. A schematic location of the thruster and the electric propulsion related instruments is shown in Figure 1. The PPS-1350 Hall effect thruster will operate at an specific impulse of 1640 seconds delivering a maximum thrust of 70 mN using Xenon gas as propellant.

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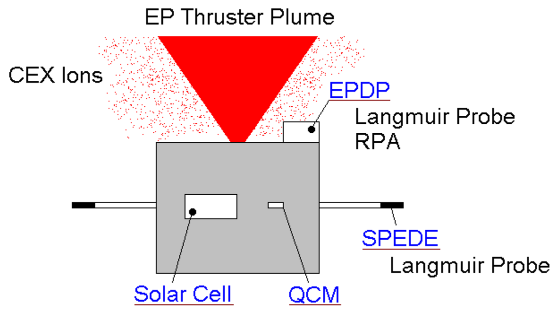

Figure 1 Schematic Instrument Location on SMART-1

Parameters	PPS-1350 Thruster
Thrust	70 mN
Voltage	350 V
Current	3.8 A
Mass Flow Rate	4.2 mg/s
Specific Impulse	1640 s
Power	1350 W
Total Efficiency	51 %
Divergence Angle	42°

Table 1 PPS-1350 Performance Parameters

During operation, the thruster emits an ion beam with a divergence of about 40°. Typical operating parameters are summarised in Table 1. Electrons from an external cathode act as a neutraliser creating a quasi-neutral plasma. Although the propellant efficiency for these type of thrusters exceed 95%, the neutral density is comparable to the beam ion density due to the much lower thermal velocities (400 m/s) compared to the ion velocities gained due to the acceleration potential of 350 V (22,500 m/s). Resonant charge-exchange collisions between the ionised and neutral effluents create slow ions that can be distributed around the spacecraft following the potential distribution in the vicinity of the spacecraft.

Several plasma sensors onboard SMART-1 will characterise the ambient plasma and the effects on the low-energy charge-exchange plasma emitted by the Hall thruster. In this section, we will give an overview of the instruments involved in the evaluation of the spacecraft/environment interactions related to electric propulsion:

2.1 Electric Propulsion Diagnostic Package (EPDP)

This package consists of four instruments outside the primary ion beam (Langmuir probe, Retarding Potential Analyser, Solar Cell Sample, and Quartz Crystal Microbalance) aiming at characterising the charge-exchange ion environment around the spacecraft[6]. The instrument requirements are summarised in Table 2.

2.1.1 Langmuir Probe

The spherical Langmuir probe is located 55 cm next to the Hall thruster (Figure 2). This sensor provides information about the plasma potential, the electron density and the temperature respectively. The charge-exchange ion trajectories are determined by the potential distribution created by space charge effects around the spacecraft. Outside the primary beam ions, the potential is composed of the space charges from the charge-exchange ions and the neutraliser electrons. Hence, the Langmuir probe data provides useful information on the electron behaviour and therefore on the potential and charge-exchange distribution near the thruster.

2.1.2 Retarding Potential Analyser (RPA)

This sensor is located next to the Langmuir probe on the same probe assembly (Figure 2). The retarding potential analyser measures the ion energy and current density distribution passing through a grid structure. The charge-exchange ion energy is of crucial importance to predict sputtering phenomena on the spacecraft surface. Only if the energy is above a certain material dependent threshold (Aluminium: 68 eV, Silicon 150 eV, Rosenberg et al, 1962), sputtering occurs. The predicted energy is in the order of several tens of Volt, below such thresholds. However, rapid changes in the spacecraft floating potential will change the energy distribution which is difficult to simulate

Physical Parameters	Instrument Requirements
Plasma Density	$10^{13} – 10^{14}$ m^{-3}
Ion Energy	0 – 400 eV
Electron Temperature	1 – 5 eV (focus on 1.7-3.5 eV)
Plasma Potential	-150 – 100 V
Ion Current Density	0.001 – 1 mA/cm^2 (focus on 0.002-0.05 mA/cm^2)
Deposition	0 – 0.44 mg/cm^2 (TBC)

Table 2 EPDP Instrument Requirements

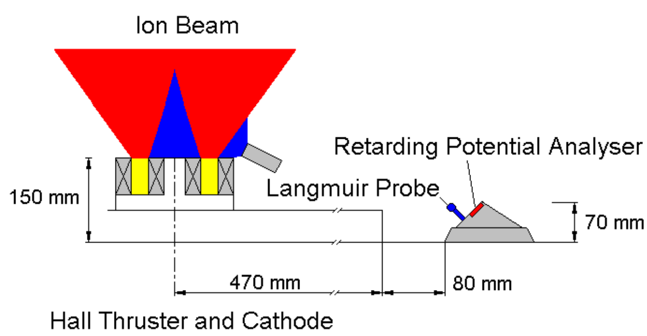

Figure 2 EPDP Location

numerically. This will not only effect sputtering, but also a change in the ion distribution leading to possible contamination of other parts than the thruster area, e.g. to the solar arrays or even instruments. A detailed analysis of the charge-exchange energy distribution at different floating potential conditions will give valuable answers to this problem.

2.1.3 Solar Cell Sample

A solar cell sample will be mounted on the –X panel of SMART-1 to study possible degradation due to the operation of the electric propulsion system (Figure 1). If power losses are observed, they also provide information of the charge-exchange ion density and energy related to sputtering of the solar cell's cover glass causing the degradation. The presence of charge-exchange ions in this location is, however, unlikely. As the simulation results in section 4 show, the charge-exchange ions are expected to expand radially from the primary ion beam. The only possible mechanism to attract ions to the solar panel location is a change in the ambient potential structure or large different floating potential conditions depending on the orbit and eclipses.

Hence, the analysis of these data is crucially linked to the Langmuir probe and the SPEDE sensors which provide information about the ambient plasma environment and the spacecraft potential, as shown later.

2.1.4 Quartz Crystal Microbalance (QCM)

This sensor is located next to the solar cell sample to monitor possible deposition of propellant ions during thruster operation (Figure 1). Deposition is especially important for optical instruments like cameras. As already mentioned above, the presence of charge-exchange ions at this location is unlikely. Similar measurements in Deep Space One indicated the presence of an charge-exchange ion flux to a Langmuir probe on the opposite side of the thruster (Wang, 1999). However, changes in the floating potential were not monitored. The flux was orders of magnitude below the solar wind flux and occurred only at certain high thrust level conditions. If sensor data appears during thruster operation, QCM data will also contribute to a better understanding of the interaction between the charge-exchange ions and the ambient plasma environment.

2.2 Spacecraft Potential, Electron and Dust Experiment (SPEDE)

The SPEDE experiment consists of two electric sensors of cylindrical shape mounted on the ends of two 60-cm booms (Figure 3). Each sensor can work either in a Langmuir (LP) mode or in an electric field (EF) mode.

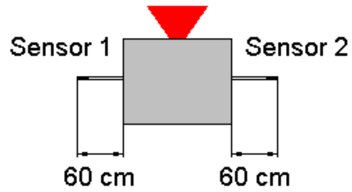

Figure 3 SPEDE Location

When operated in an EF mode, the sensor is current-biased, and both the spacecraft potential and wave electric fields can be monitored. As already pointed out, large variations in the spacecraft potential affect the charge-exchange ions distribution. These measurements will aid the analysis of possible contamination detected by the solar cell sample and the QCM. Also, gas molecules absorped on the spacecraft will later be slowly desorped, resulting in enhanced plasma wave activity[7].

Using the potential measurement of an EF sensor and the electron temperature from the EPDP Langmuir probe, we can even estimate the charge-exchange ion density, assuming a Boltzmann energy distribution of the neutralising electrons.

In an LP mode, the sensor is voltage-biased in order to monitor the variation of the electron flux. An increase of the electron flux would also indicate the presence of charge-exchange ions in a quasi-neutral plasma.

3. Spacecraft/Environment Modelling for SMART-1

Both EPDP and SPEDE perform single-point measurements of the charge-exchange ion environment produced by the Hall thruster. Therefore, a numerical model is necessary to predict the whole plasma environment around the spacecraft and to interpret and relate the obtained measurements. A 3D Particle-In-Cell (PIC) model treating ions and neutrals as computer particles and electrons as a fluid was developed and verified using available ground testing data. The detailed model description can be found in Tajmar et al, 2001[4].

Typical simulation parameters are a grid size of 100x100x100 and up to 1,500,000 particles. Computations require one day on a standard PC workstation.

4. Simulation of the SMART-1 Plasma Environment

In this section we will show some initial modelling results of the SMART-1 plasma environment due to the operation of the Hall thruster. Before evaluating the influence of the Hall thruster plume on the whole spacecraft, we will look at the ion and neutral densities from the thruster only on a x-y plane as shown in Figures 4 and 56 respectively. The simulation domain was 1x1x1 m with no background pressure to resemble a vacuum environment. In the neutral density plot, we clearly see the asymmetry due to the propellant flowing through the cathode located on the right side of the thruster. This influences the production of charge-exchange ions as shown in Figure 45 coming out from the primary ion beam. Because most charge-exchange collisions will occur at locations where the ion and neutral density are at their maximum, most of the collisions are expected to occur close to the thruster's exit ring and near the cathode. The slow ions, initially having only thermal velocities, will then follow the potential distribution around the thruster. In our physical model we assumed a quasi-neutral plasma and derived the potential from the ion density. Looking at the ion density plot in Figure 4, we note a maximum near the thruster's exit ring and a density build up at the thruster's axis 10 cm above the spacecraft surface. This is characteristic for a ring type emission. Similar to the ion density build up, also a potential hump is expected in our quasi-neutral plasma model. Hence, the charge-exchange ions below the potential hump will be deflected towards the spacecraft surface, all other slow ions will be more radially deflected parallel to the spacecraft surface. Figure 6 plots the backflow structure on the surface using an even smaller domain size of 0.4x0.4x0.4 m. Most backflow ions are concentrated on the inner ring thruster area. They originate from the ion density maximum at the thruster's exit deflected by the potential hump and the positive space charge from the primary beam ions. On the right side of the peak, we also note an asymmetry due to the cathode's neutral density peak.

Figure 7 plots the ion density on a x-z plane through the middle of the thruster and the SMART-1 spacecraft including the solar arrays. In the middle of the thruster, the ion density reaches a value of $1x10^{17}$ m^{-3}. The charge-exchange ions radially leave the beam creating an ion density 5 orders of magnitude less than at the thruster's exit. Most important, we see that the ion's space charge is not sufficient to expand the ion beam down in the direction of the solar arrays. This shows that the operation of the Hall thruster does not cause contamination to the spacecraft other than at the top surface where the thruster is located.

This simulation has been computed assuming an initial spacecraft floating potential of 0 Volt. As already mentioned above, fast transients in the potential can influence the distribution of the charge-exchange ions. However, due to our initial assumption of a quasi-neutral plasma used to derive the potential distribution, charged surfaces can not be treated in this code. This would require to solve the potential at every time step using the charge density on the grid and the boundary conditions on the surface which is computationally very

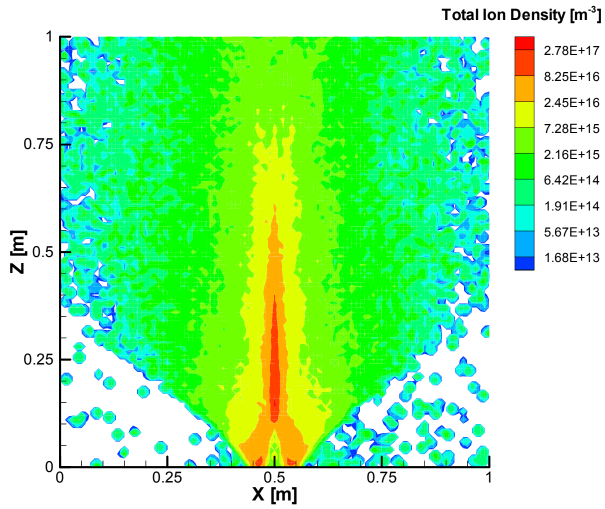

Figure 4 Total Ion Density Plot

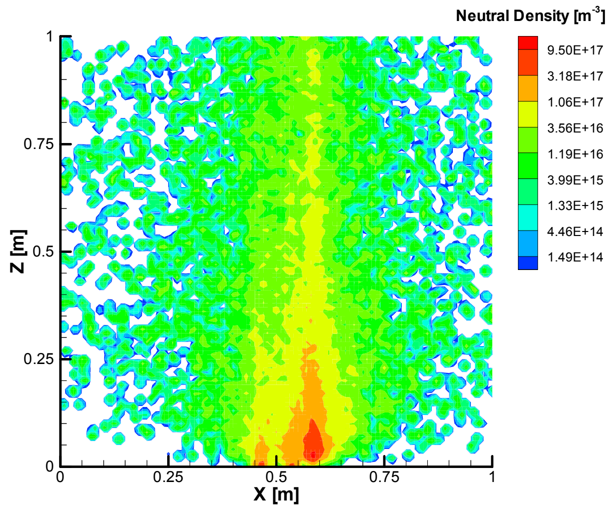

Figure 5 Neutral Density Plot

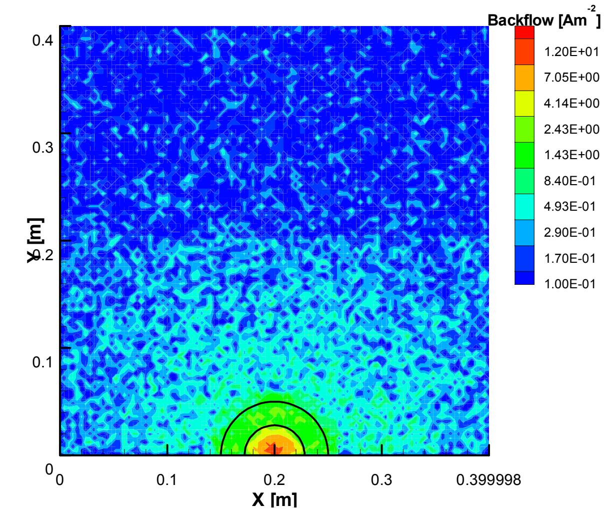

Figure 6 Backflow Current Distribution

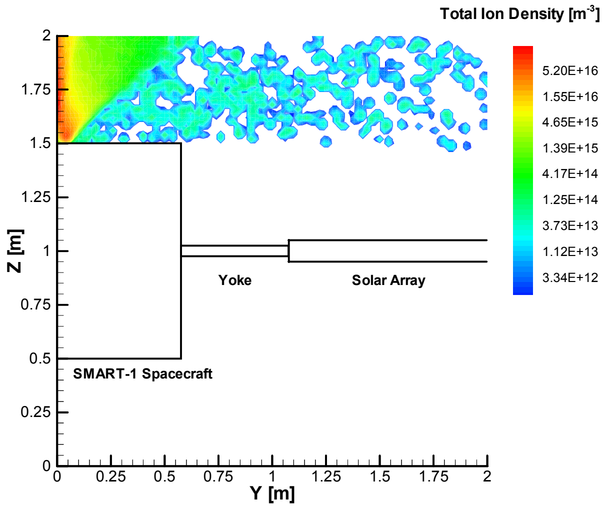

Figure 7 y-z Plot of Ion Density through middle of SMART-1

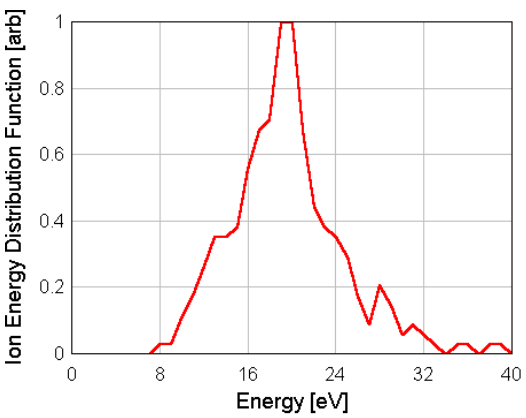

Figure 8 Virtual EPDP-RPA Sensor

expensive[8]. If flight data may reveal such fast potential transients and accordingly an impact of charge-exchange ions at sensors outside the top surface. In that case, a new modelling approach would be necessary to avoid quasi-neutrality. Since code verifications with ground test data was successful using the quasi-neutrality assumption, the present numerical model does not address problems related to fast spacecraft floating potential transients.

The ions will form a space charge potential hump in front of the thruster which will deflect the charge-exchange ions. Virtual plasma sensors were implemented in the simulation to compare with ground tests and in-flight measurements. As an example, Figure 8 shows the data of the virtual RPA sensor from the EPDP next to the ion beam.

It is a function of the potential distribution and maximum potential built up in front of the thruster. The data shows a peak around 20 eV going down to a maximum of 35 eV. The 20 Volt peak corresponds to the potential hump in front of the thruster[4]. This data suggests no sputtering on the spacecraft surface (Aluminium has a sputter threshold of 68 eV).

5. Conclusion

SMART-1 will be the first interplanetary spacecraft using a Hall thruster. Two plasma experiments (EPDP, SPEDE) will assess the change of the plasma environment around the spacecraft before, during and after the operation of the thruster. A 3D PIC-MCC code has been developed to study spacecraft/environment interactions related to the SMART-1 mission. The code is capable of simulating the Hall thruster on the spacecraft geometry including virtual sensors to simulate the plasma instruments.

Preliminary modelling data assuming a quasi-neutral plasma suggests that the ion beam will not influence parts of the spacecraft other than the top surface where the thruster is located. The peak energy of the charge-exchange ions flowing back to the surface was found to be 20 eV. This is well below the sputter yield threshold of Aluminium, the material of the spacecraft surfaces.

A successful validation of the model with in-flight data will provide mission designers with a very powerful tool to study spacecraft/environment interactions for Hall thrusters.

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