EP plasma plume in orbit: Diagnostics and analysis correlation

IEPC-2019-294

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

J. Laube[1], N. Massaccesi[2], B. Zitouni[3], and M. Peukert[4]
OHB System AG, Universitätsallee 27-29, Bremen, D-28359, Germany

and

M. Naeije[5]
Delft University of Technology, Kluyverweg 1, Delft, 2629 HS, Netherlands

As a large system integrator OHB currently realizes several satellite missions using electric propulsion for orbit control and transfer. These systems generate highly energetic ions within the plasma plume, which can degrade the spacecraft surfaces under impingement. Therefore, extensive system level analyses have to be performed to ensure proper spacecraft performance over the entire lifetime. The current paper presents the plasma modelling techniques used at OHB for the prediction of the plasma plume expansion in orbit and shows the validation of the methods to several experimental data sets under different environmental conditions. Finally, the meaning of these validations for the plume impingement analyses at OHB is shown and the planning of further in orbit experiments is presented.

I. Introduction

Electric propulsion (EP) currently experiences an increased use for space applications. The reasons for that are the well-known advantages of high ISP and thus low propellant consumption to generate the necessary Δv for spacecrafts. Due to its relatively low thrust, up to now EP has been mainly used for orbit control maneuvers of satellites, which allow for a low Δv generated over an elongated timeslot. One of the EP technologies with certainly most mission heritage is the conventional Hall Effect Thruster (HET), which has flown on a multitude of satellite missions up to now [1]. However, new technologies have been developed like the high-efficiency-multistage-thruster (HEMPT) [2], the gridded-ion thruster (GIT) [3], or many others which exhibit different advantages. In addition, new concepts like magnetic shielding [4] are often discussed for the use with Hall-Effect-Thrusters.

Furthermore, large thrusters with Power consumptions $\geq$ 3 kW and thrust values $\geq$ 150 mN have been used in recent missions to additionally perform the orbit transfer of satellites from their insertion orbit to the final (e.g. geostationary)

[1] Propulsion Engineer, Propulsion systems, jens.laube@ohb.de.
[2] Master-Student, Propulsion systems. Master thesis as part of the Masters Degree "Aerospace Engineering", at the Faculty of Aerospace Engineering at Delft University of Technology
[3] Propulsion and Environment Analysis Expert, Propulsion systems, Bayrem.zitouni@ohb.de.
[4] Head of Department, Propulsion systems, markus.peukert@ohb.de.
[5] Assistant Professor, Faculty of Aerospace Engineering, m.c.naeije@tudelft.nl.

orbit. Especially these full-EP missions save large quantities of propellant mass compared to chemical-propulsion-missions, which can be used for an increased payload mass of the spacecraft. Finally, even larger thrusters or arrays of thrusters are developed to accomplish future space-exploration missions [5] [6].

As a large system integrator, OHB is currently realizing two different satellite missions using electric propulsion. The Heinrich-Hertz (H2Sat) mission uses EP for station keeping maneuvers and will first apply two of the German HEMPT thrusters for an in-orbit demonstration of the technology. As redundant system, two HETs are also applied in the mission. The Electra mission [7] (Fig. 1) will be a full-EP satellite, using four 5 kW HETs for the orbit transfer and for station keeping maneuvers.

One shortcoming of electric propulsion is the generation of highly energetic ions in the plasma-plume of the thruster, which can degrade the spacecraft surfaces, when impinging them. The thruster plume in fact expands towards the surrounding space and hits also spacecraft surfaces, which are not accommodated directly in front of the thruster. Rather, it has been shown that ions can even move to angles larger than 90° from the thruster-axis [8]. This impingement can lead e.g. to the erosion of the cover glass surfaces of heat-radiators or solar cells on the solar arrays, which results in decreased light transparency of the cover glass and reduction of performance. Furthermore, the over-critical erosion of the metallic interconnectors between the solar cells can lead to loss of the electric connection and thus to loss of the entire cell or string of cells. The erosion of surface material then leads to the secondary effect of surface contamination with eroded material. The deposited material changes the surface properties of the underlying materials, which can lead to undesired effects. Accordingly, the contamination has an impact on the performance of again the radiators, of orbit-control sensors, payload-optics and RF-reflectors.

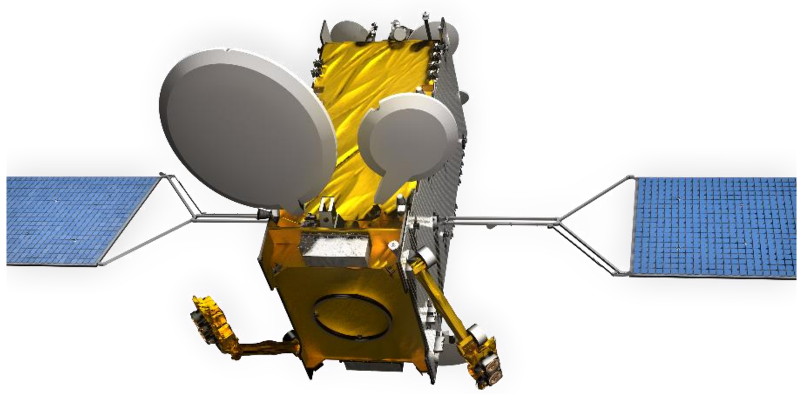

Figure 1. Electra satellite. Artist-impression ©OHB

Due to this reason, extensive plume analyses have to be performed during the design-phase of an EP-satellite to ensure a proper performance of the spacecraft surfaces under EP-plume impingement. As a first step, this task requires a precise prediction of the plasma-plume expansion in orbit, which determines the amount and energy of the ions reaching a certain surface. However, the plasma dynamics inside the plasma plume, and with this also the expansion of the plume depend on several boundary conditions, which differ between space and Earth. The most prominent driver of the plume expansion is the so-called charge-exchange (CEX) collisions [1]. In these collisions, ions exiting from the thruster collide with surrounding neutral gas molecules and transfer their charge to the neutral. This leads to a fast moving neutral atom at the speed of the former ion and a slow moving ion. This slow ion is then accelerated by the plasma potential gradient away from the plume center and moves towards large angles from the thruster-axis. The frequency of the CEX collisions depends mainly on the neutral gas pressure, which tremendously differs between the vacuum in space and the atmosphere on Earth. To overcome this difference, usually extensive plume tests are performed in large vacuum chambers, which shall represent the in-space vacuum as good as possible. However, the vacuum pressures, which can be reached during the thruster operation in the on-ground tests is still above the in-orbit conditions. On top of that further boundary conditions deviate between the tests and the application, like the wall potential or the influence of space-weather. This requires for an extrapolation method between the on-ground and in-orbit conditions.

OHB uses a hybrid Particle-in-Cell method to simulate the plasma plume under different conditions. In this method, the ions and neutrals are simulated as particles, which allows adapting the neutral gas pressure, the plasma potential shape and the wall potentials among others. As the method uses several empirical parameters, it has to be validated against test data under different conditions to prove its capability for prediction of in-orbit behavior.

In the following Section II, the used methods are described in more detail. Section III deals with the results of several plasma simulations and their validation against different on-ground and in-orbit experiments. Furthermore, the application of the method to ongoing satellite projects of OHB and the planning for further in orbit experiments is presented in this section. Section IV presents conclusions from the paper.

II. Methods

The plasma simulations described in this paper have been carried out with PICPluS (Particle In Cell Plume Simulator) [9], which applies a hybrid Particle-in-Cell method. It simulates the ions and neutrals as superparticles containing in the order of 10^8 ions/atoms per particle. CEX and elastic collisions between the particles are computed via a Monte Carlo Collision (MCC) method creating ions at the former neutral velocity or at a recombined velocity respectively. The electrons are modelled analytically on the grid-nodes of the simulation domain. To this aim, the plasma is assumed to be quasi-neutral, leading to the same amount of positive and negative charges n_e and n_i within every cell:

$$n_e = n_i$$

By further assuming adiabatic expansion of the electron gas

$$T_e = T_{e,0}\left(\frac{n_e}{n_{e,0}}\right)^{\gamma-1}$$

with the electron temperature T_e, the reference electron temperature $T_{e,0}$, the reference electron number density $n_{e,0}$ and the adiabatic exponent γ, the simplified electron momentum equation can be solved for the plasma potential:

$$\varphi = \varphi_0 + \frac{k_B T_{e,0}}{q}\frac{\gamma}{\gamma-1}\left[\frac{n_e}{n_{e,0}} - 1\right]$$

with the reference plasma potential φ_0, reference electron temperature, and reference electron number given at the thruster-exit plane respectively. The particle charge is given by q. This simplification of the electron interaction enables a significant increase of computation speed, while still providing good agreement to experimental plasma measurements outside of the thruster chamber [10]. The ions represented by charged particles then interact with the plasma potential on the grid-nodes via

$$m\frac{dv}{dt} = -q\nabla\varphi$$

This simulation method has been applied several times before and yields good results for the simulation of the plasma-plume of EP thrusters [11] [12] [13].

For the plume impingement analysis on spacecraft level, the plasma plume predicted by the above described simulation method is then loaded to the ray-tracing tool openPlumeEP [14] [15]. This tool has been developed at OHB and provides a fast and easy-to-use ray-tracing method for distances above 0.5 m to the thruster-exit, where the ion trajectories do not change significantly any more. In openPlumeEP, the injected ion energies and current densities are extrapolated towards the spacecraft surfaces and combined with material sputter-, reemission- and accommodation-laws to model the surface erosion, contamination and disturbance forces.

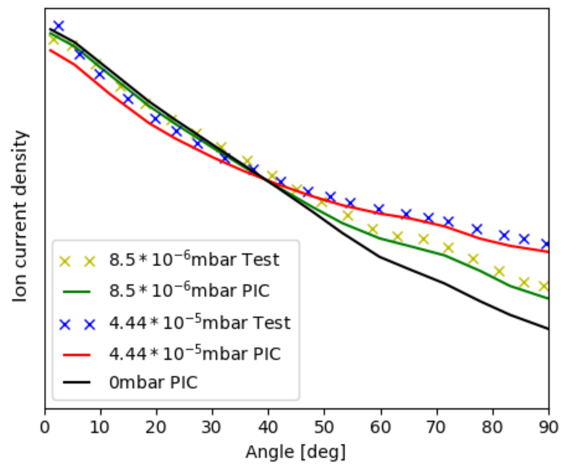

Figure 2. Ion current density vs. angle to the thruster-axis.

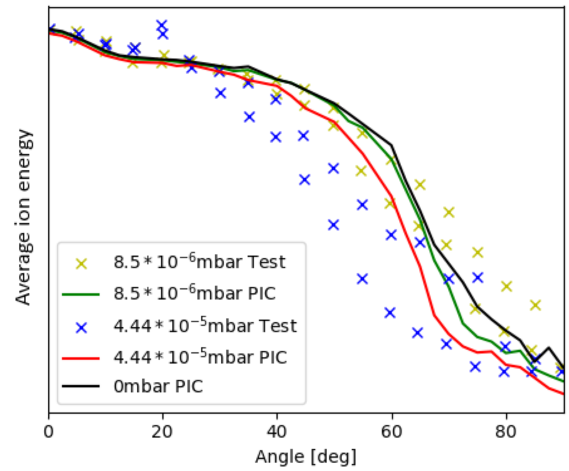

Figure 3. Average ion energy vs. angle to the thruster-axis.

III. Results

A. Simulation of on-Ground plasma plume

To analyse the plume impingement of a typical EP thruster for station keeping, the plasma plume of an SPT100 Hall-Effect-Thruster has been simulated. For these simulations, the nominal thruster operation point with an anode voltage of 300 V and a Xenon mass-flow of 5.5 mg/s has been used. In Fig. 2, the resulting ion current density is compared to experimental test data at different pressures. It can be seen that decreasing the chamber pressure leads to a higher ion current density in the center of the plume and to a lower current density at large angles. This behavior can be easily explained by the decrease of the density of the neutral atoms and thus by a decrease of the charge-exchange collisions in the chamber. The hybrid PIC simulations do not only represent the current density trend with increasing angle but also follow the same trend as the experiments for varying pressure. Figure 3 shows the average energy from the same tests and simulations. It can be seen that the PIC simulations represent the experimental data again to a very good extend. As for the ion current density, also here the decreasing chamber pressure has an impact on the plasma-plume by slightly increasing the average energy. The smaller number of slow CEX ions shifts the average energy to slightly higher values. From both simulation results at total vacuum, which represent the in-space conditions, it can be seen that the plume still changes from the lowest chamber pressure to in-space conditions. Although this trend leads to a less stringent plume in space, the change should still be considered for a proper plume impingement analysis to avoid over-design of the spacecraft.

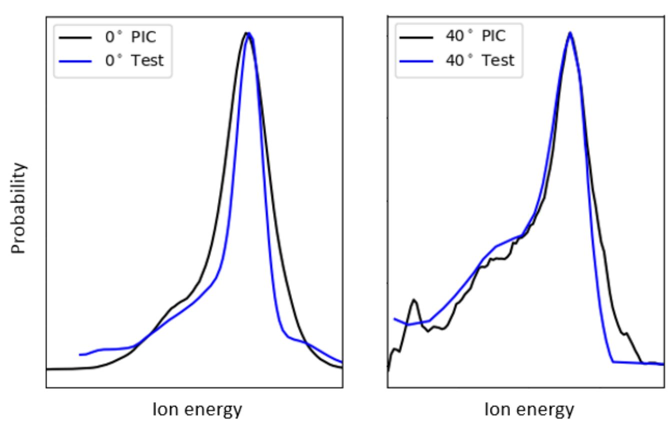

Figure 4. Ion energy distribution for an angle of 0° to the thruster-axis (left) and of a medium angle to the thruster-axis (right).

Figure 4 shows two single ion-energy distribution curves, demonstrating that not only the average ion energy, but also the energy distributions coincide between the experiments and simulations.

B. In-Orbit Validation

As mentioned in the introduction, not only the density of the neutral atoms changes in space but also other boundary conditions of the plasma. Furthermore, in the previous section, it has been shown that the plasma plume still changes from the

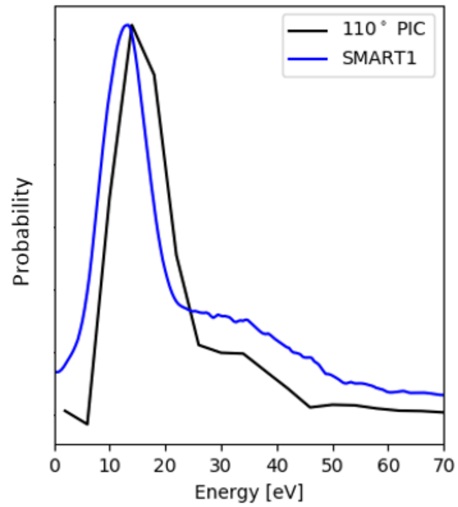

Figure 5. Ion energy distribution as measured on SMART-1.

lowest chamber pressure of the on-ground tests. Due to this fact, some missions in the past have been equipped with in-orbit experiments, to test the variation of the plasma-plume between ground and in-orbit conditions [16] [17] [18]. The SMART-1 mission used a PPS1350 Hall-Effect-Thruster for its main propulsion system. Together with the EP system, an Electric Propulsion Diagnostic Package (EPDP) was accommodated on the spacecraft to measure the ion energy and ion current density at an angle of approximately 110° to the thruster-axis and at a distance of 0.6 m to the thruster-exit. The Express-A mission used eight SPT100 thrusters for station keeping maneuvers and applied several sensors to measure the ion current density and ion energy of the plasma plume. Two sensors were accommodated on the solar array edges leading to a variable angle and distance of the sensors to the thruster, while two sensors were accommodated statically at high angles to the thruster. The sensors were applied to the two Express-A missions #2 and #3.

In order to correctly predict the in-orbit plume, the results of the PIC simulations are validated in this section against these experiments. Figure 5 shows the ion energy distribution from the SMART-1 mission [19] and the corresponding PIC simulation. It can be seen that even for angles above 90° ions are reaching the surfaces. The energy distribution is dominated by the low energy ions from the CEX collisions, which exhibit an energy maximum at approximately 14 eV. But there are also some ions exhibiting energies of 40 to 50 eV, which needs to be accounted for in a plume impingement analysis, as these energies are above the sputter threshold of most materials.

In Fig. 6, the ion current density measured during the Express-A missions is shown [18]. It can be seen that the current density from the PIC simulation agrees well to the experimental data at very small and large angles but overestimates experimental data at intermediate angles. The reason for this is probably a non-optimal alignment of the probes on the solar array with the thruster at intermediate angles, which leads to shadowing of the sensor detector and loss of ions at the sensor walls. Note that some sensor data at an angle of approximately 76° have been taken out from the comparison.

Figure 7 shows a comparison between the ion energy distributions measured on Express-A and simulated by PIC at a small angle from the thruster axis. It becomes clear that, even if the average and peak energy match between the

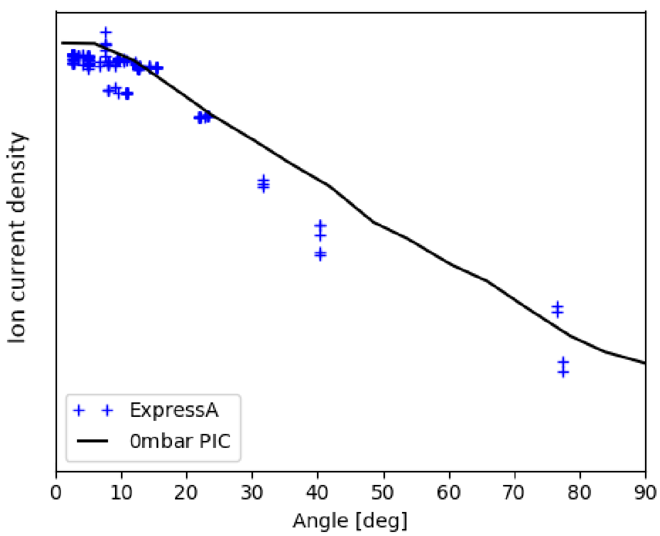

Figure 6. Ion current density from the Express-A mission.

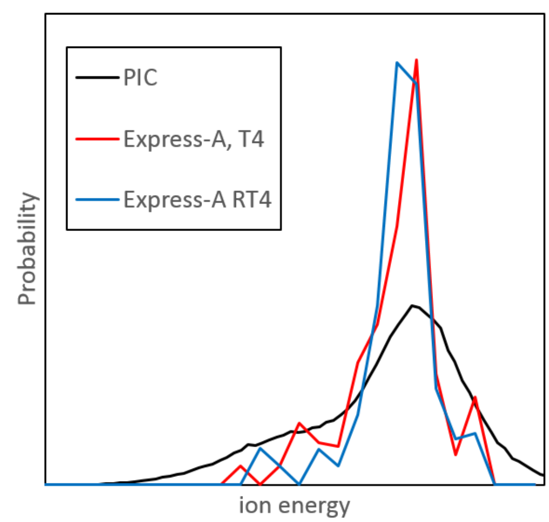

Figure 7. Ion energy distribution measured at the Express-A mission at an angle of approximately 0° to the thruster-axis.

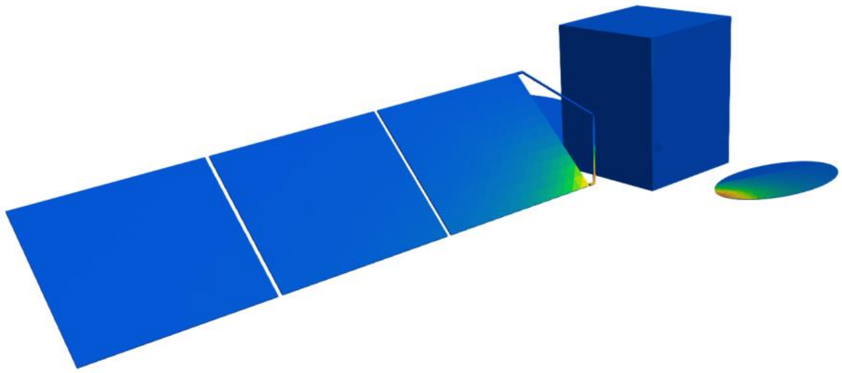

Figure 7. Ion flow from a Hall-Effect-Thruster to spacecraft surfaces on an OHB mission. The colors show low to high ion current to the surface from blue to red.

simulations and experiments, contrary to the Ground case, the measurements exhibit a much more narrow distribution than the simulations. It is not clear, if this deviation results from a measurement artefact of the sensors or from a difference between the plasma conditions inside the thruster between the operation on Ground and in orbit. One possible explanation for this difference could be a shift of the acceleration and ionization regions as is also seen elsewhere for varying background pressures [20]. Furthermore, the ion energy distributions measured at other solar array-angles, where the sensor surface normal does not point directly towards the thruster-exit, exhibit much larger deviations from the simulations due to the above mentioned effect of the sensor field of view. Finally, the measurements of the ion energy distribution of the thrusters T3 and RT3 exhibit a significant downshift of the energy peak by approximately 30 to 40 eV. The thruster RT3 has shown a much lower thrust in orbit than during the Ground acceptance tests [18], so the shift of the ion energy could be a hint to the thruster misbehavior.

The above described different width of the energy distribution, the different sensor signal, when not pointing directly towards the thruster-exit and the different ion energies for the engines with lower thrust need to be investigated in more detail and will be subject to further studies at OHB in the future.

C. EP plume in OHB missions

The above findings for the SPT-100 and PPS1350 plume behavior are directly applied to the plume impingement analyses of OHB spacecrafts. In Fig. 7 an example of the ion current flow from such a Hall-Effect-Thruster to the solar array during a station keeping maneuver of an OHB satellite is shown. It can be seen that most of the ions impinge the solar array edges due to the rotation of the panel. The extensive validation of the HET plasma plume simulations against different conditions are used to decrease the design margins against plume impingement. This leads to more efficient spacecrafts being still safe against degradation from the EP plume.

Furthermore, new EP thruster types are currently being implemented on OHB spacecrafts. Similar validation campaigns like shown above for the on-ground data are also performed for these thrusters and the insights from the above comparison to in-orbit results are used for the development of the plume models. However, no in-orbit proof of these models exists, which leads to the use of more conservative plume models for these types of thrusters to ensure a safe performance of the satellite. Especially the testing of the large thrusters with a power of 3-5 kW is difficult in the existing vacuum facilities and leads to chamber pressures, which are one order of magnitude higher than for the 1.5 kW class thrusters shown above. Due to this, the gap between the lowest achievable testing pressure and the in-orbit vacuum is high, leading to some uncertainty for the extrapolation and thus to more conservative models. The decrease of these margins is one of the challenging tasks in the next years for OHB.

D. Future in-orbit experiments

As mentioned in the section above, the application of EP thruster technologies where the plume has not been measured in orbit is connected to some uncertainty and leads to more conservative spacecraft designs. Therefore, OHB participates in the development of a new Electric Propulsion Diagnostic Package (EPDP), to be implemented on OHB satellites. This package is capable of measuring the ion energy, current density, plasma potential, plasma density and electron temperature in the plasma plume. Furthermore, the package is equipped with an erosion sensor, which is capable of measuring the silver erosion resulting from the plume impingement at the solar array. A more detailed description of the package can be found in Ref [21]. One possible application of the package is the H2Sat mission as can be seen in Fig. 8. The mission will fly in 2022 and will use the HEMPT thruster and a HET thruster for station keeping maneuvers. The characterization of the HEMPT will then lead to a significantly reduced design margin, when implementing the thruster technology on a spacecraft.

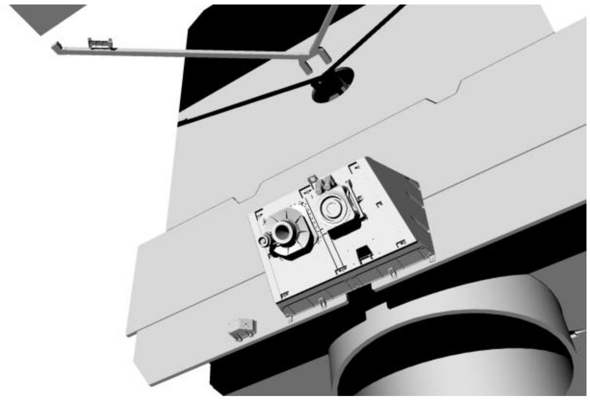

Figure 8. Implementation of the EPDP on the H2Sat mission.

IV. Conclusion

It has been shown that the hybrid PIC approach allows for a proper prediction of the EP plasma plume under different environmental conditions. This capability is used at OHB to develop plume models for the plume impingement analysis on spacecraft level. The extensive validation against in-orbit measurements leads to a less conservative plume model and thus to a more efficient spacecraft design. However, discrepancies exist between the simulations and some in-orbit measurement results, which could be either due to sensor issues or hint towards a change of the plasma conditions inside the thruster chamber from Ground to orbit. This needs to be investigated further to understand better the influence of the space boundary conditions.

Furthermore, even for the small 1.5 kW Hall-Effect-Thrusters operated in a large vacuum chamber, the chamber pressure is still higher than under space conditions leading to a change of the expansion of the plasma plume between testing and application. Testing of larger thrusters used for orbit raising missions leads to chamber pressures that are one order of magnitude higher than in the case of small thrusters. This leads to a large gap between the ground tests and the in space application that needs to be bridged by simulation. Advanced plume simulations are therefore becoming much more important for the use of large EP thrusters and new thruster technologies.

In-orbit measurements which are performed directly under the conditions of the thruster application are very useful for validation of plume simulations. It is clear that such experiments are necessary especially for new thruster technologies and for large thrusters. Therefore, OHB participates in the development and application of such in-orbit experiments.

Acknowledgments

The authors would like to thank all colleagues at OHB System for their support and the EPIC project within the Horizon 2020 framework programme of the European Union for funding of parts of the work.

Funded by the Horizon 2020
Framework Programme of the
European Union

References

[1] D. M. Goebel and I. Katz, *Fundamentals of electric propulsion: Ion and Hall thrusters.*, Oxford: Wiley, 2008.

[2] E. Bosch and et al., "Status of HEMPT-NG development programme at Thales Ulm," in *the 36th International Electric Propulsion Conference, Vienna, Austria, IEPC-2019-822*, 2019.

[3] H. Leiter und et al., „The Ariane Group Electric Propulsion Program 2019-2020,“ in *the 36th International Electric Propulsion Conference, Vienna, Austria, IEPC-2019-592*, 2019.

[4] I. G. Mikellides and et al., "Magnetic shielding of a laboratory Hall thruster. I. Theory and validation," *Journal of Applied Physics*, vol. 115, 2014.

[5] J. Cassady and e. al., "The Importance of Electric Propulsion to Future Exploration of the Solar System," in *the 36th International Electric Propulsion Conference, Vienna, Austria, IEPC-2019-711*, 2019.

[6] M. J. Glogowski and et al., "Application of SOlar Electric Propulsion in the Emerging Satellite Servicing Industry," in *the 36th International Electric Propulsion Conference, Vienna, Austria, IEPC-2019-753*, 2019.

[7] V. Garcia, "EP system development and functional validation tests for the Electra GEO satellite," in *the 36th International Electric Propulsion Conference, Vienna, Austria, IEPC-2019-288*, 2019.

[8] L. B. King, "Transport-property and mass spectral measurements in the plasma exhaust plume of a Hall-Effect space propulsion system." Ph.D. Dissertation, Ann Arbor, MI USA: Department of Aerospace Engineering, University of Michigan,, 1998.

[9] A. Passaro, A. Vicini and F. Nania, "Validation Status of the PICPluS Plume Simulation and Spacecraft Interaction Tools: Lesson Learnt from Flight and Ground Experimental Data," in *the 30th International Electric Propulsion Conference, Florence, Italy, IEPC-2007-325*, 2007.

[10] K. Dannenmayer and S. Mazoufre, "Electron flow properties in the far-field plume of a hall thruster.," *Plasma Sources Science and Technology,* vol. 22(3), no. 1, 2013.

[11] B. Zitouni and et al., "Next generation plume modelling and its impact on S/C design," in *Space Propulsion Conference*, Rome, 2016.

[12] B. Zitouni and et al., "Electric Propulsion Plume Modelling: OHB approach," in *the 35th International Electric Propulsion Conference, Atlanta, Georgia, USA, IEPC-2017-135*, 2017.

[13] J. Laube and et al., "EP plasma plume: Modelling, validation status and way forward," in *Space Propulsion Conference*, Seville, 2018.

[14] B. Zitouni and et al., "openPlume, new concept for next generation EP plume modelling," in *Space Propulsion Conference*, Seville, 2018.

[15] B. Zitouni and et al., "Thrusters modelling, propellant choice and plume expansion: openPlumeEP capabilities," in *the 36th International Electric Propulsion Conference, Vienna, Austria, IEPC-2019-211*, 2019.

[16] G. Matticari and et al., "The SMART-1 Electric Propulsion Diagnostic Package," in *3rd International Conference on Spacecraft Propulsion*, Cannes, 2000.

[17] D. L. Estublier, "The SMART-1 Spacecraft Potential Investigations," *IEEE TRANSACTIONS ON PLASMA SCIENCE,* vol. 36, no. 5, 2008.

[18] D. Manzella and et al., "Hall Thruster Plume Measurements On-board the Russian Express Satellites," in *the 27th International Electric Propulsion Conference, Pasadena, California, USA*, 2001.

[19] J. Gonzales del Amo and e. al., "Spacecraft/thrusters interaction analysis for Smart-1," in *the 29th International Electric Propulsion Conference, Princeton, New Jersey, U.S.A. IEPC-2005-003*, 2005.

[20] A. Lopez Ortega and et al., "Numerical investigatons of Background Pressure Effects and CHannel Erosion in the SPT-140 Hall Thruster for the Psyche Mission," in *the 36th International Electric Propulsion Conference, Vienna, Austria, IEPC-2019-211* , 2019.

[21] T. Trottenberg and et al., "Development of a Flight Electric Propulsion Diagnostic Package (EPDP) for EP Satellite Platforms," in *the 36th International Electric Propulsion Conference, Vienna, Austria, IEPC-2019-345*, 2019.