The Assessment of Interactions between Spacecraft and Electric Propulsion Systems Project

IEPC-2011-028

Presented at the 32nd International Electric Propulsion Conference, Wiesbaden, Germany September 11–15, 2011

Matías Wartelski*, Carlos Ardura† and Christophe Theroude‡
Astrium Satellites, Toulouse, 31400, France

Alexander Reissner§
FOTEC Forschungs- und Technologietransfer GmbH , 2700 Wiener Neustadt, Austria
Korea Advanced Institute of Science and Technology, Daejeon 305-701, South Korea

Martin Tajmar¶
University of Applied Sciences Wiener Neustadt, 2700 Wiener Neustadt, Austria
Korea Advanced Institute of Science and Technology, Daejeon 305-701, South Korea

and

Eric Gengembre‖
European Space Agency, ESTEC, 2201AZ Noordwijk ZH, The Netherlands

The "Assessment of Interactions between Spacecraft and Electric Propulsion Systems" (AISEPS) project, funded by ESA and carried out by a consortium led by Astrium Toulouse, aims at developing a system tool for simulation of interaction between spacecraft and electric propulsion systems. The chosen approach consists in the implementation of electric thrusters plume models into Spacecraft Plasma Interaction System (SPIS), which is a freeware and open-source software. The objective is to simulate thruster's plume and spacecraft charging consistently, taking into account the neutraliser electric configuration in order to reproduce the Cathode Reference Potential (CRP). In a first step, FOTEC has created an electronic Plume Database gathering relevant public plume data for SPT100, PPS1350, PPS5000, T5, T6, RIT4, RIT10, RIT22, HEMP3050, Indium and Cesium FEEP thrusters. Also, the influence of the test facility on plume characteristics and CRP of a miniaturised μN-RIT thruster has been studied but is presented in a specific paper. Using the database, plume models for all the mentioned thrusters have been implemented in SPIS, tuned and validated. The plume models show excellent match of experimental data in the plume axis and very satisfactory agreement in the backflow region. The Plume Database and the new version of SPIS will be available at the end of the project.

*Modeling Engineer, Space Physics Team, Matias.Wartelski@astrium.eads.net.
†Trainee, Space Physics Team, Carlos.Ardura@astrium.eads.net.
‡Head of Engineering Products and Tools Team, ACE84, Chrishtophe.Theroude@astrium.eads.net.
§Research Scientist, Department of Aerospace Engineering, Alexander.Reissner.fl@fotec.at / Ph.D. Candidate, Department of Aerospace Engineering, areissner@kaist.ac.kr.
¶Head of Aerospace Engineering Department, Martin.Tajmar@fhwn.ac.at / Associate Professor, Department of Aerospace Engineering, Martin.Tajmar@kaist.ac.kr.
‖Technical Officer, Electric Propulsion Section, Eric.Gengembre@esa.int.

Nomenclature

C	=	temperature constant in adiabatic law
γ	=	adiabatic constant
e	=	elementary charge
η_p	=	fraction of doubly-charged ions
η_u	=	ionization efficiency
η_c	=	cathode split
$FWHM$	=	full width at half maximum of a gaussian distribution
k_B	=	Boltzmann constant
$\dot{m}$	=	total mass flow rate
$\dot{m}_i^+$	=	singly-charged ion mass flow rate
$\dot{m}_n$	=	neutral mass flow rate
n_i, n_{ref}	=	local and reference ion density
Φ_p, Φ_{ref}	=	local and reference plasma potential
T	=	thrust
T_e, T_n	=	electron and neutral temperature
$U_{emitter}$	=	emitter potential
U_{exit}	=	potential within the ion beam at the level of the accelerator electrode
v_+, v_{++}, v_n	=	velocity of singly and doubly-charged ions and neutrals

I. Introduction

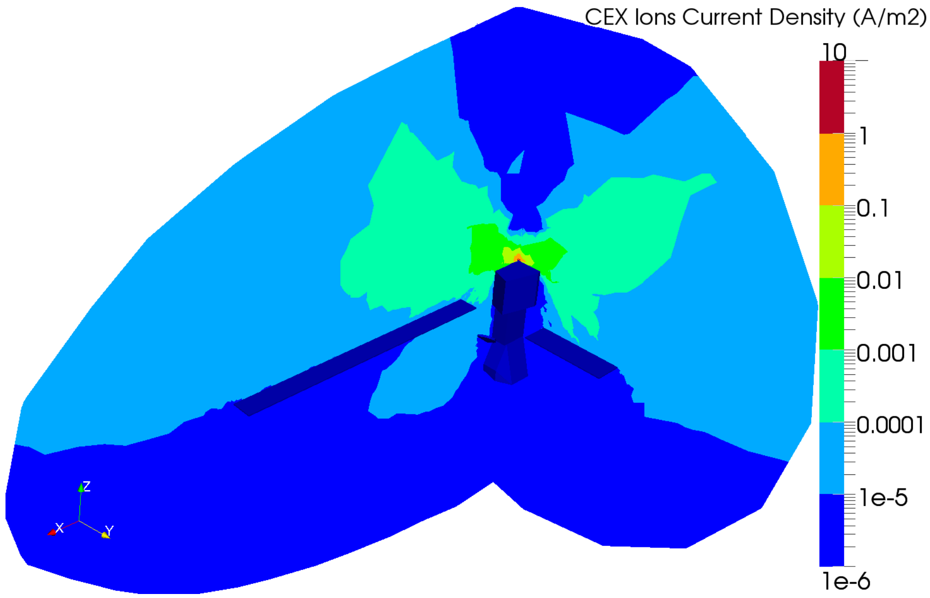
Electric propulsion is undoubtedly a promising technology already being used aboard European spacecraft. However, the interaction between the exhausted ions and electrons with the spacecraft raises challenging and complex problems for system engineers. One critical problem is erosion of sensitive materials by energetic ions and subsequent contamination of other spacecraft surfaces. Another problem is that, depending on the electric configuration of the thruster and neutraliser (grounded or floating), the recollection of electrons and ions by spacecraft elements may increase the electron current emitted by the neutraliser thus reducing its operational life-time. The plasma cloud created by electric thrusters around the spacecraft can also have advantages, like reduction of electrostatic discharge risk by smoothing differential potentials. All together requires a tool for prediction of these effects during design phases.

The objective of the AISEPS project is to develop a system tool capable of simulating thruster plume and spacecraft charging at the same time and consistently, taking into account interaction properly. This paper begins with an overview of the AISEPS project and its status. Section III introduces the method developed to simulate the plume of different thrusters. Finally, section IV shows validation of the implemented plume models. The experimental part of the project is detailed in another paper[6].

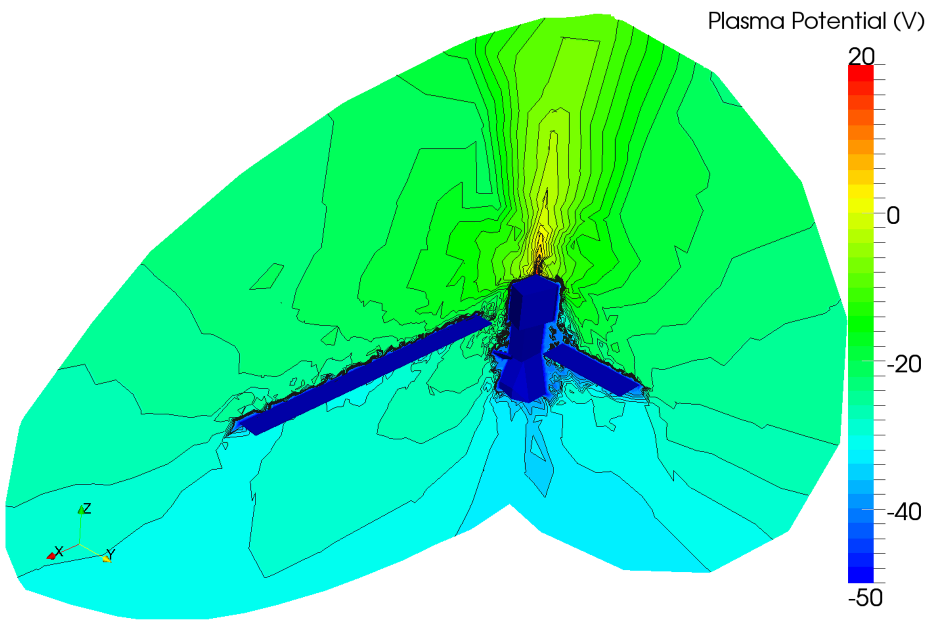
II. Overview of the AISEPS project and status

The first work package of the project has been carried out by FOTEC (formerly Austrian Institute of Technology). It consisted in an bibliographical review of published electric thruster's plume data concerning the following thrusters: Hall effect thrusters (SPT100, PPS1350, PPS5000), ion thrusters (T5, T6, RIT4, RIT10, RIT22), HEMP3050 and FEEP thrusters (Indium and Cesium). All the relevant data have been gathered into an electronic database called the European EPT's Plume Database. Fotec has also proposed plume models for all thrusters.

The second work package, carried out by Astrium GmbH, the University of Gießen and the Electric Propulsion Laboratory at ESTEC, consisted in making plume measurements of a μN-RIT thruster (RIT-4) in the Corona test chamber at ESTEC. The test focused on studying the influence of background pressure and electric configuration of the neutraliser not only on plume characteristics but also on the Cathode Reference Potential (CRP). The experimental setup and test results are presented in Ref. 1. The third task, being carried out by Astrium Toulouse, consists in the development of a system tool for simulation of the



(a) CEX current density



(b) Plasma potential

Figure 1. T6 plume flow field around Bepi-Colombo with a ground absolute potential of -50 V.

interactions between spacecraft and electric thrusters. This task is subdivided in three work packages: firstly, implementation, tuning and validation of the plume models specified by FOTEC; secondly, validation of the system tool, in particular for CRP prediction, using data from the μN-RIT test; finally, application of the system tool to predict the plasma environment of the SMART1, Bepi-Colombo and Small-GEO spacecraft during electric thrusters firing.

At this stage, the implementation, tuning and validation of plume models is finished. They can already be used to obtain the plume flow field around a spacecraft with fixed potentials. Figure 1 shows, for example, the T6 plume flow field around the Bepi-Colombo spacecraft with a fixed absolute potential of -50 V. The system tool validation and interaction modeling is still on-going and is out of the scope of this paper.

III. Simulation Method

The SPIS software[2] is an open-source free-ware tool for 3D simulation of interaction between plasma and spacecraft taking into account spacecraft absolute and differential charging (see Ref. 3 for a presentation of SPIS and Ref. 4 for its up-to-date capabilities). Plasma simulation is based on the Particle-in-Cell (PIC)[5] method. Nevertheless, SPIS offers the possibility to switch between different versions of the PIC method like full-PIC or hybrid-PIC, where electrons are simulated as a fluid. At the same time, spacecraft charging is calculated using an equivalent electric circuit and taking into account interaction with its surrounding plasma. Figure 2 presents a sketch of SPIS simulation structure. At the lowest level, particle populations are simulated taking into account electric and magnetic fields, whereas the electric field is solved taking into account the plasma flow field; at the highest level, currents between plasma and spacecraft are computed and used by a circuit solver to obtain spacecraft potentials, whereas spacecraft potentials are used by the plasma solver as boundary conditions.

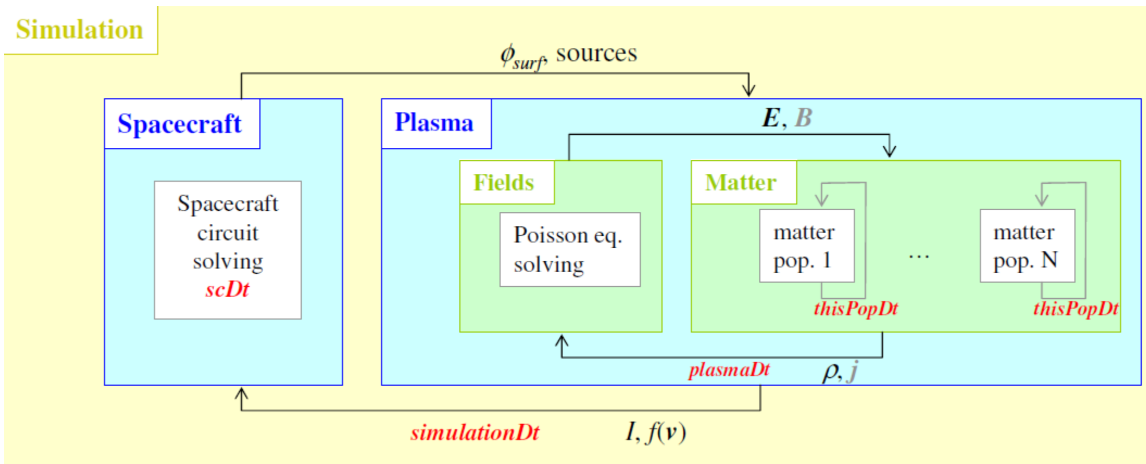


Figure 2. Sketch of SPIS simulation structure (taken from Ref. 20).

The plume models implemented in SPIS in the frame of AISEPS are based on the approach used in the SMART-PIC code[6]. Only ions and neutrals are simulated with PIC particles, whereas electrons are modeled as a fluid. The potential can be obtained solving the Poisson equation or assuming quasi-neutrality together with the Boltzmann relation. Fast ions are injected into the simulation volume from a source surface corresponding to the thruster exit surface. Because interaction often occurs in the far field and in the backflow region, and because the plume models are intended for system analysis, the objective was to match experimental data in these two regions. Accordingly, the injection profile or initial conditions of fast ions do not necessarily reproduce accurately near field data. The plume models were initially proposed by FOTEC, implemented by Astrium in SPIS and finally tuned using experimental data. The next paragraphs present the plume models philosophy whereas parameters specific to each thruster are provided in section B.

A. Potential Solver

In SPIS, the standard method to calculate the electric potential is solving the linear or non-linear Poisson equation[3]. For high density plasmas like those in the plume of most electric thrusters, the quasi-neutrality assumption gives nearly the same results as solving the Poisson equation (see Ref. 7) and it is faster and more stable. Therefore, it has been chosen to implement in SPIS[a]. the quasi-neutrality equations with constant or variable electron temperature. The user can nevertheless switch between the Poisson solver and the quasi-neutrality approach from the SPIS Graphical User Interface (GUI). If the quasi-neutrality approach with constant electron temperature is selected, the plasma potential is calculated from Eq. 1,

$$\Phi_p = \frac{k_b \cdot T_e}{e} \cdot ln \frac{n_i}{n_{ref}} + \Phi_{ref}. \tag{1}$$

[a]This has been done with technical support from ONERA

The Boltzmann relation only holds for isothermal, unmagnetized and collisionless electrons. In order to include variation of the electron temperature in a simple manner, an adiabatic electron model has been implemented, shown in Eq. 2

$$k_B \cdot T_e \cdot n_e^{1-\gamma} = C \tag{2}$$

where γ and C are derived experimentally (see Ref. 8). In this case, the plasma potential is calculated using Eq. 3

$$\Phi_p = \frac{k_b \cdot \gamma \cdot T_{e,ref}}{e(\gamma-1)}[(\frac{n_i}{n_{ref}})^{\gamma-1}] + \Phi_{ref}. \tag{3}$$

Quasi-neutrality has been used to solve the flow field electric potential of HET, ion and HEMP3050 thrusters, whereas the Poisson solver has been used in the case of FEEP thrusters.

B. Injection Models

1. HET and Ion thrusters

All the particles corresponding to the same ion population are injected with the same speed. In the case of Hall effect thrusters, the velocity angle with respect to the source surface normal varies linearly, as a function of radial position: at the inner boundary of the channel it takes the value α_{left} and at the outer boundary the value α_{right} (see figure 3). Ion thrusters have circular exit surfaces, so the velocity angle varies linearly between the surface center, where it takes the value 0, and the outer boundary where it takes the value α_{right}.

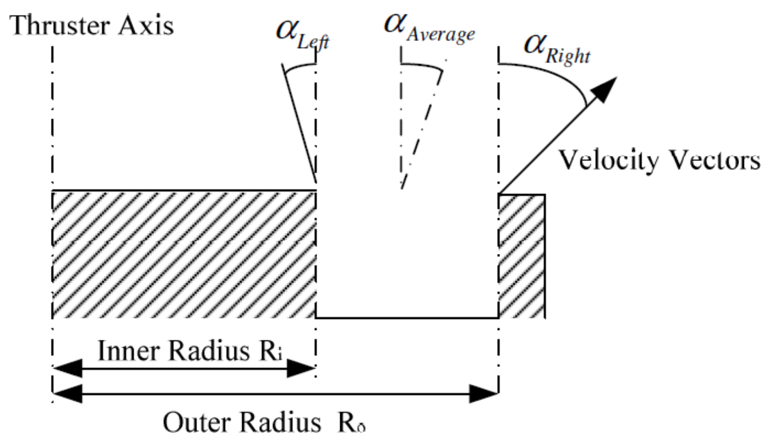


Figure 3. Injection model for HET.

Ions are injected with speeds given by Eq. 4 and Eq. 5 respectively

$$v_+ = \frac{T(1+\eta_p\sqrt{2})}{\dot{m}\cdot\eta_u(1-\eta_c)(1+2\cdot\eta_p)(sin(\alpha_{av})/\alpha_{av})^2} \tag{4}$$

$$v_{++} = \sqrt{2}\cdot v_+ \tag{5}$$

and the following mass flow rates

$$\dot{m}_i^+ = \frac{\dot{m}\cdot\eta_u(1-\eta_c)}{1+\eta_p\sqrt{2}} \tag{6}$$

$$\dot{m}_i^{++} = \eta_p\sqrt{2}\dot{m}_i^+ \tag{7}$$

where $\alpha_{av} = (\alpha_{left} + \alpha_{right})/2$.

For hall effect thrusters, the ion density is taken uniform over the source surface whereas for the other thrusters it follows a gaussian distribution.

Regarding neutrals, the background population is simulated with an analytical constant pressure and temperature. The neutral plume emitted by the thruster can be simulated in SPIS either with an analytical lambertian distribution or with PIC particles. In the latter case, neutrals are injected with thermal speed given by Eq. 8 and the velocity angle follows a cosine distribution over the surface. Neutral density also follows a cosine distribution over the surface and the neutral mass flow rate is given by Eq. 9,

$$v_n = \sqrt{\frac{8 \cdot k_B \cdot T_n}{\pi \cdot m_n}} \tag{8}$$

$$\dot{m}_n = \dot{m}[\eta_c + (1-\eta_u)(1-\eta_c)]. \tag{9}$$

2. HEMP3050

The injection model is the same as for ion thrusters and the only change is the calculation of injection speeds and mass flow rates, given by the following equations,

$$v_+ = \frac{T}{\dot{m} \cdot \eta_u(1-\eta_c)(sin(\alpha_{av})/\alpha_{av})^2} \tag{10}$$

$$v_{++} = v_+ \tag{11}$$

$$\dot{m}_i^+ = \frac{\dot{m} \cdot \eta_u(1-\eta_c)}{1+\eta_p} \tag{12}$$

$$\dot{m}_i^{++} = \eta_p \cdot \dot{m}_i^+. \tag{13}$$

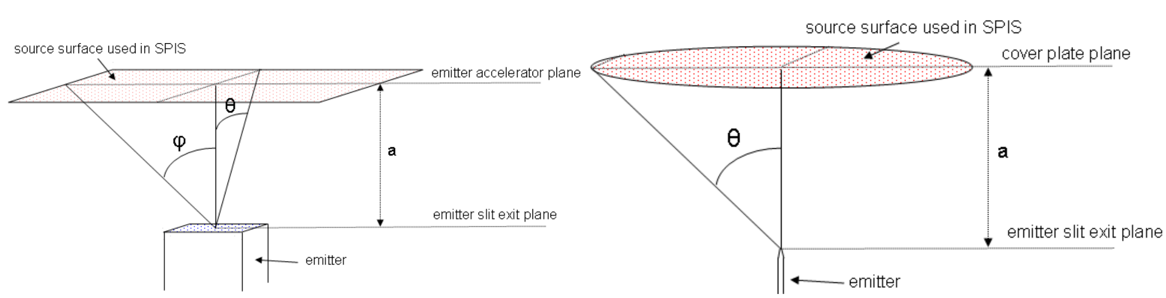
3. Indium and Cesium FEEP

In the case of FEEP thrusters, only the main ion species, Ce^+ and In^+ respectively, are simulated. The source surface in SPIS corresponds to the cross-section of the ion beam at the emitter accelerator plane and cover plate plane respectively (see figures 4(a) and 4(b)) and not the emitter slits which are too small. The ion speed and mass flow rate are given by Eq. 14 and Eq. 15 respectively,

$$v_+ = \sqrt{\frac{2(U_{emitter} - U_{exit})e}{m_i}} \tag{14}$$

$$\dot{m}_i^+ = \frac{i_{beam}}{e \cdot m_i}. \tag{15}$$

In the Indium FEEP model, the velocity angle varies linearly between the source surface center and the boundary, exactly as with ion thrusters. Cesium FEEP source surface is rectangular, so two boundary angles are needed: in this case, it is the angle of velocity projections the two surface directions which vary linearly. The ion and neutral densities follow a cosine and uniform distributions respectively over the source surface. Neutral particles are injected with thermal velocity whose angle follows a cosine distribution.



(a) Cesium FEEP (b) Indium FEEP

Figure 4. Definition of source surface for a Cesium FEEP.

C. Charge-exchange collisions

Most of interaction between electric thruster's plume and spacecraft is due to slow charge-exchange ions generated by an electron exchange between slow neutral particles and fast ions. At creation, these ions have the neutral thermal velocity, so they are slow enough to be attracted by spacecraft surfaces, generally charged negatively. For thrusters using Xenon, only the following two charge-exchange collisions have been simulated,

$$Xe^{+}_{fast} + Xe_{slow} \rightarrow Xe_{fast} + Xe^{+}_{slow} \tag{16}$$

$$Xe^{++}_{fast} + Xe_{slow} \rightarrow Xe_{fast} + Xe^{++}_{slow}. \tag{17}$$

Currently, only the Monte-Carlo Collision (MCC) method[5] is implemented in SPIS. The Xe_{fast} particles are not simulated and the Xe_{slow} particles are not modified by collisions. Ion-ion and ion-neutral elastic collisions are ignored. Taking this mechanism into account requires much more computational effort and previous work[9] has shown that, for an SPT-100, the difference in results between both methods is significantly smaller that the uncertainty on flow parameters at the thruster exit plane. The cross-section values are specified in SPIS in a tabulated text file. The used cross section, based on measurements published in Ref. 10, is calculated using Eq. 18,

$$\sigma_{CEX}(\Delta v) = a - b \cdot ln\Delta v \tag{18}$$

where Δv is the relative velocity of the two particles and the two parameters a and b are derived by fitting experimental curves. Currently, SPIS neglects the velocity of the neutral particles and Δv is taken equal to the velocity of the colliding ion. For (Xe^{+}, Xe) collisions, the used constants are $a_1 = 1.71 \cdot 10^{-18}$ and $b_1 = 1.18 \cdot 10^{-19}$, whereas for (Xe^{++}, Xe) collisions, the constants are $a_2 = 1.03 \cdot 10^{-18}$ and $b_1 = 7.7 \cdot 10^{-20}$.

IV. Results

A. Plume Database

It has already been mentioned that lot of public experimental plume data concerning the electric thrusters included in the AISEPS project has been gathered and ranged into the European Thrusters Plume Database. This tool offers fast access to lot of plume data: by selecting one thruster, one measured parameter and one varied parameter (x-axis), as shown in figure 5, the user obtains the list of requested available data. For each dataset, it also provides very useful information concerning the related experimental setup like chamber background pressure or measuring probe type and size. Besides, it contains some model data as well. The data can be either plotted or exported to text files. This database can be enriched and completed with new data.

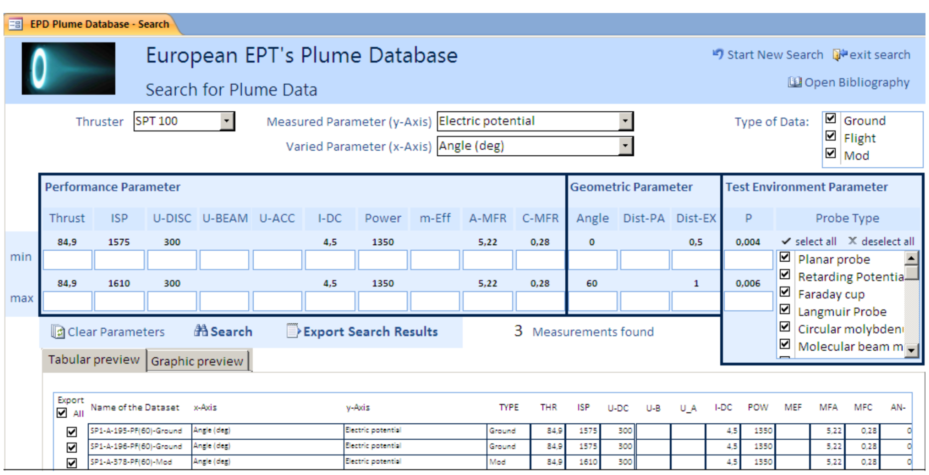


Figure 5. Example of data search in the Plume Database.

B. Plume Model Validation

An extensive campaign of plume model tuning and validation has been carried out using all relevant data in the European EPT's Plume Database. The philosophy of the plume models has already been introduced in section III. The parameters of the plume models, together with some geometrical parameters, are presented in tables 1 and 2. Because the current version of SPIS does not output ion energy distribution, the presented plume models have been tuned and validated above all in terms of current density profile. It is not excluded to optimize them if new capabilities, like output of ion energy distribution or elastic collisions computation, are implemented in SPIS, or if new plume data is published. Indeed, all the plume model parameters presented in tables 1 and 2 are accessible through text files so that future users can modify and adapt them according to the specific characteristics and data of the thruster to be modeled. Two values in table 1 need clarification.

Parameter	SPT100	PPS1350	RIT4	RIT10	RIT22	T5	T6	HEMP3050
Inner Radius (m)	0.028	0.03	-	-	-	-	-	-
Outer Radius (m)	0.05	0.05	0.02	0.0435	0.105	0.05	0.11	0.057
Left angle (deg)	-12	-12	0	0	0	0	0	3.4
Right angle (deg)	40	44	20	8.5	21	12	-36	48
Mass Flow (mg/s)	5.5	6.7	$5 \cdot 10^{-3}$	0.61	4	0.67	3.5	1.8
Thrust (N)	0.0849	0.107	$7.5 \cdot 10^{-5}$	0.02	0.175	0.018	0.145	0.044
η_p	0.1	0.2	0.01	0.01	0.01	0.05	0.21	0.45
η_u	0.95	0.9	0.38	0.74	0.85	0.77	0.85	0.8
η_c	0.05	0.08	0.05	0.05	0.05	0.148	0.08	0.12
Ion Dens. Distrib.	Unif	Unif	Gauss	Gauss	Gauss	Gauss	Gauss	Gauss
FWHM	-	-	0.9	0.995	1.1	0.7	0.46	0.9

Table 1. Tuned Parameters of Hall effect, ion and HEMP thrusters.

Parameters	Cesium FEEP	Indium FEEP
Emitter-accelerator distance (mm)	0.6	13
Emitter Voltage (V)	6000	4500
Exit Voltage (V)	0	0
Ion divergence angle (deg)	46x4	20
Ion current (mA)	1	$8.5 \cdot 10^{-6}$
Geometrical angles (see figure 4)	$\theta = 30$, $\phi = 15$	$\theta = 25$
Ion Density Distribution	cosine	cosine

Table 2. Tuned parameters of FEEP thrusters.

Firstly, a negative right angle is used for T6 because, contrary to the other thrusters, the virtual source point is positioned around 18 cm in front, and not behind, of the exit surface, as mentioned in Ref. 11. This is both due to the convex form of the grid and to its ion optics. And secondly, the HEMP3050 model uses a non null left angle although the source surface is circular. This creates a discontinuity of the injection velocity angle at the center of the source surface. However, it allows reproducing the drop of far field current density in the plume axis, see figure 6(c). This drop is attributed to the magnetic field topology[b], which is not included in the implemented plume models.

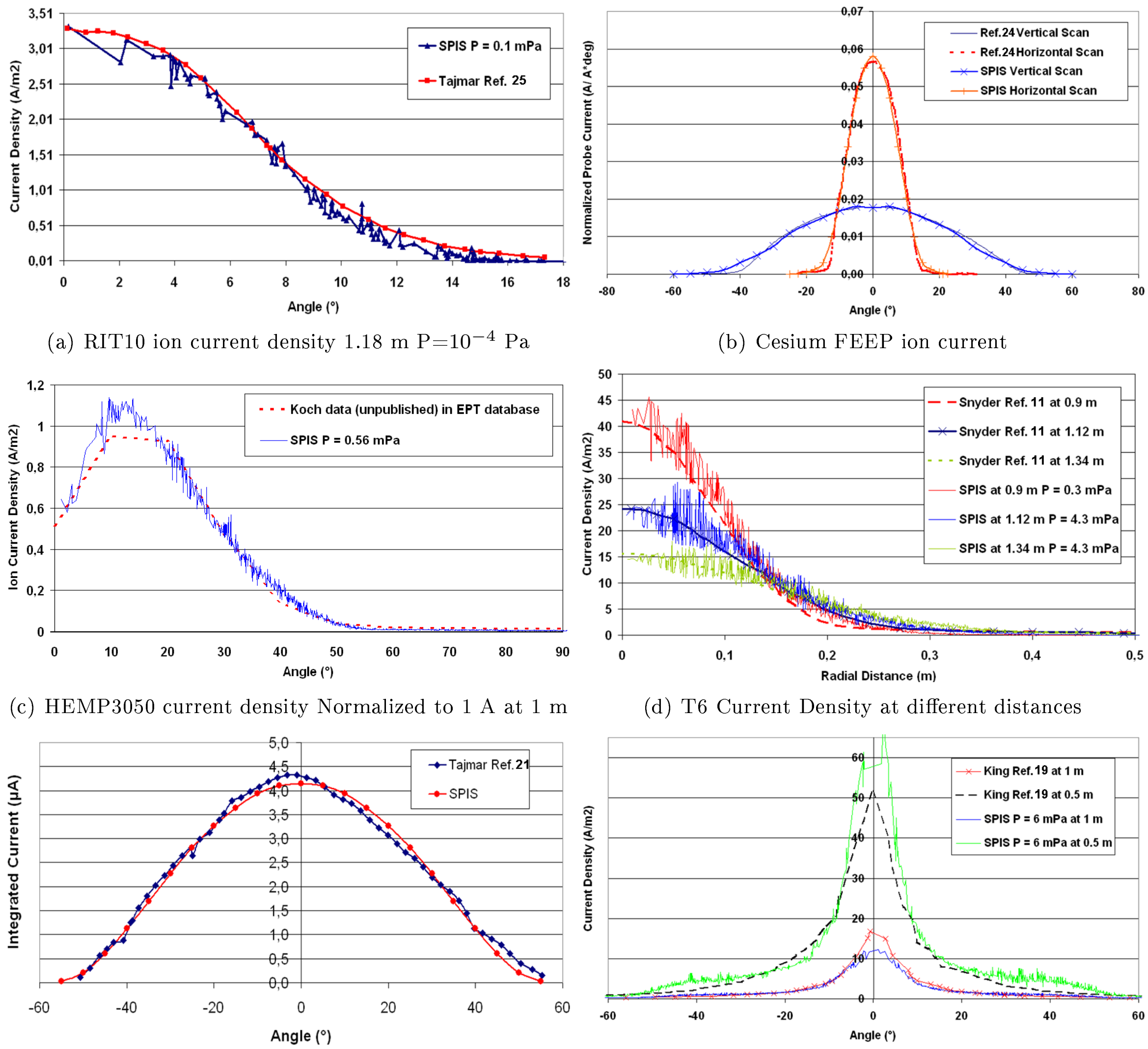
Validation of plume models is generally divided in two parts: the main beam, which strongly depends on the injection conditions; and the backflow region, which is directly related to collisions modeling, in particular CEX. Fitting experimental backflow data is the most difficult task but it requires, firstly, a good modeling of the main beam. Due to the great number of thrusters, only some relevant results and conclusions

[b]Private communication with Norbert Koch, March 2011

are presented hereafter. It must be pointed out that the PPS5000 model has not been tuned nor validated because there is not sufficient experimental data.

1. *Main beam*

All other plume models fit very well measured current density data in the main beam region. Figure 6 shows excellent agreement between ion current simulated with SPIS and measured data for RIT10, Cesium and Indium FEEP, HEMP3050, SPT100 and T6 thrusters. It must be noted that the noise on simulated data is mainly due to the unstructured mesh in SPIS.



(a) RIT10 ion current density 1.18 m P=10^{-4} Pa

(b) Cesium FEEP ion current

(c) HEMP3050 current density Normalized to 1 A at 1 m

(d) T6 Current Density at different distances

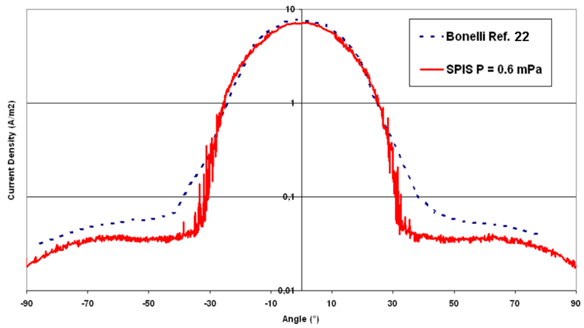
(e) Indium FEEP ion current

(f) SPT100 current density

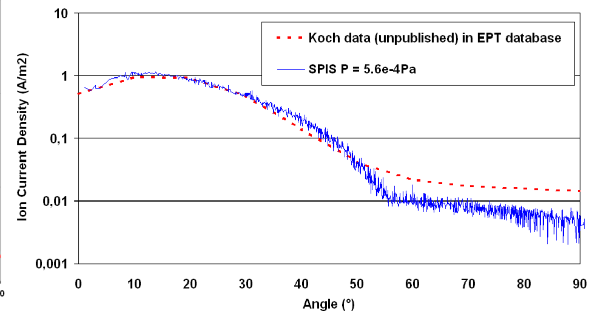
Figure 6. Comparison between simulated and measured ion current in the main beam region.

2. *Backflow region*

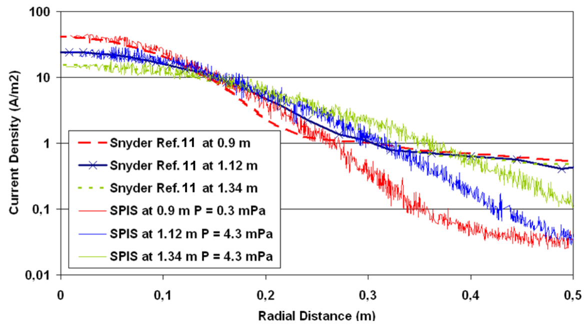
Regarding the backflow region, the following plume models have been validated: SPT100, PPS1350, RIT22, HEMP3050 and T6. CEX collisions are neglected in the case of Indium FEEP: Ref. 12 estimated the CEX current to be of the order of 1% of the ion current, which is already very low. No data was available at high angles for Cesium FEEP and RIT10. Finally, the RIT-4 model will soon be tuned and validated using the backflow measurements realised in the frame of AISEPS to be published in Ref. 1.



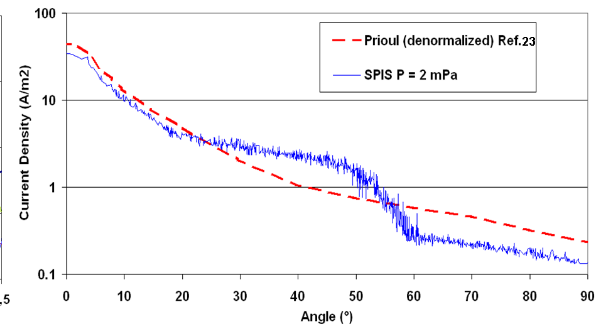
(a) RIT22 current density at 1m



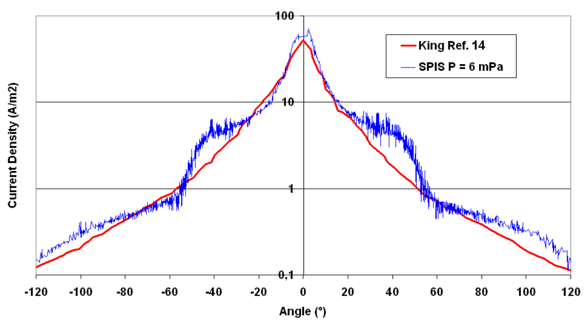
(b) HEMP3050 current density normalized to 1 A at 1 m



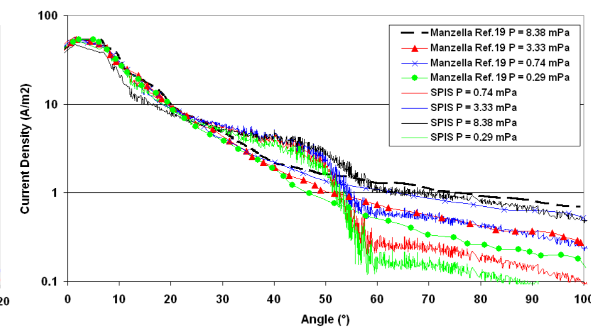
(c) T6 current density at 0.9 m



(d) PPS1350 current density at 0.7 m



(e) SPT100 current density at 0.5 m compared with King data



(f) SPT100 current density at 0.6 m compared with Manzella data

Figure 7. Comparison between simulated and measured current density in the backflow region.

Figure 7 presents simulated and measured current densities of RIT22, HEMP3050, T6, PPS1350 and SPT100 thrusters, in log scale, which allows to appreciate the degree of correlation at high angles. In this region, the population of CEX ions is dominant. SPIS matches the experimental trend of measured data at high angles except for T6. Table 3 gives the ratios of simulated to experimental current densities at high angles. They show that predicted CEX current is on the same order of magnitude as measured one except for T6 at the lowest pressure.

Figures 7(b), 7(d) and 7(e) show a hump on the simulated data in the 30-50 degrees region, followed by a drop. Because elastic collisions are not simulated, fast ions are found only in the main beam region. This is the reason for the abrupt transition between this region, where current density is totally dominated by fast ions, and the backflow region where, in SPIS, current density is generated only by CEX ions. Elastic collisions are considered to be the cause for the presence of high energetic ions at high angles[13,14]: it probably smooths down the transition between the two plume regions and in principle increases the backflow current. Indeed, PIC-DSMC codes[15,16,17] taking into account ion-neutral collisions usually obtain smoother decreases of current density as a function of angle.

On the other hand, it is difficult to interpret experimental data at high angles, where current density is very low. In this region, there is lot of uncertainty on plume data due to pollution by the experimental

Thruster	Ratio
RIT22	1.5
HEMP3050	3.5
T6	3-10
PPS1350	2
SPT100	1.3-2.7 (Manzella) 0-0.6 (King)

Table 3. Ratio of experimental to simulated backflow current density.

setup, in particular stagnant plasma according to Ref. 15. Indeed, integration of current densities measured by Manzella[18] between -100 and 100 degrees gives the following total currents: 4.69 A, 5.26 A, 5.97 A and 6.15 A respectively at 0.29 mPa, 0.74 mPa, 3.3 mPa and 8.8 mPa background pressures. As pointed out by Oh et al[15], this is theoretically impossible because SPT100 discharge current is only 4.5 A. Moreover, the additional current increases as background pressure increases. It seems clear that plume data is very much polluted by the setup. Figure 7(c) shows that T6 current density measured between 0.3 and 0.5 m from the plume axis does not decrease when distance to the thruster increases, which is unexpected for a thruster plume. This suggests, again, that plume data, at high angles, is polluted by the facility. Besides, backflow current density simulated in SPIS is very sensitive to the specified background pressure. The problem is that background pressure in vacuum chambers is not uniform.

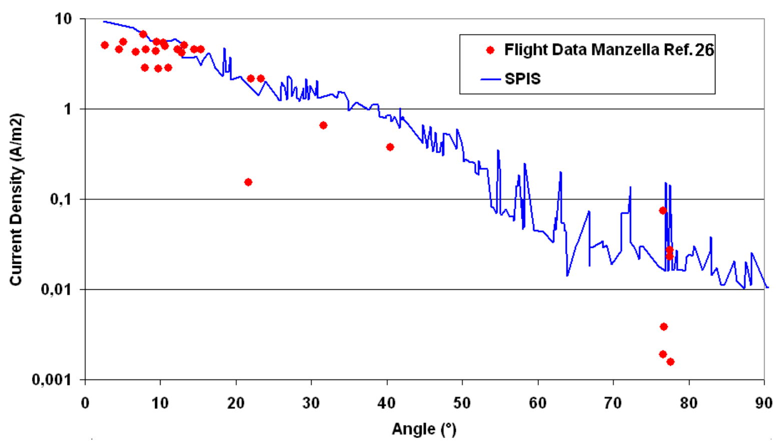


Figure 8. Comparison between simulated and in-flight SPT100 current density.

Indeed, comparison with in-flight data at high angles, see figure 8, shows that our simulations do not necessarily underestimate backflow current density. It must be reminded that the final objective is to predict backflow current under flight conditions. Because very little in-flight data is available, plume models are always validated using on-ground test data. Unfortunately, plume data at high angles is influenced by the facility, as already outlined. Consequently, extrapolation of plume models from on-ground to in-flight conditions must be performed with extreme caution. Either the degree of pollution of the used on-ground data is considered to be negligible, which is clearly not the case, for example, of SPT100 data published by Manzella[18]. Or the test facility pollution mechanisms are understood and simulated in order to isolate the thruster plume effects: to the knowledge of the authors, this requires very heavy approaches combining different methods and tools[19] and still lot of effort on ground characterisation and modeling[20]. Indeed, the RIT-4 thruster test in the frame of AISEPS[1] aims at investigating the influence of the facility on the thruster plume.

In a nutshell, plume models not taking into account elastic collisions and the precise vacuum chamber configuration have been implemented in SPIS. They are sufficiently simple and accurate for system analysis. **Measured and simulated backflow current densities are in the same order of magnitude. Given the high degree of uncertainty on experimental data in this plume region, this a very**

satisfactory result.

V. Future work and ways forward

The AISEPS project is still on-going. On one hand, the results of the RIT-4 test are going to be used to challenge the capacity of SPIS, with the newly implemented plume models, to predict the CRP and reproduce on-ground test configurations. This includes implementation in SPIS of neutraliser models for CRP and neutraliser current prediction. At the same time, the ability and different methods of SPIS to correctly predict ion and electron currents to spacecraft surfaces is being studied. The final step will be to simulate the Bepi-Colombo, SMART1 and SmallGEO plasma environment during electric thruster firing.

VI. Conclusion

In the frame of the AISEPS project, plume models, based on the PIC-MCC method, have been implemented in SPIS for the following thrusters: SPT100, PPS1350, PPS5000, T5, T6, RIT4, RIT10, RIT22, HEMP3050, Indium and Cesium FEEP. Published experimental and model data concerning these thrusters have been gathered in an electronic European EPT's Plume Database. Using this tool, all plume models except PPS500 have been tuned and validated in terms of current density. They fit very well experimental data in the main beam region, except for an abrupt transition to the CEX region. T5, RIT10 and Cesium FEEP models have not been validated in the backflow region because no corresponding data was found. Predicted models for SPT100, PPS1350, T6, RIT22 and HEMP3050 thrusters produce backflow current densities in the same order of magnitude and with the same trends as measured ones.

PPS5000 plume data and measurements in the backflow region for RIT10, T5 and Cesium FEEP are needed for tuning of plume models. Future experimental measurements in the this region should assess carefully the influence of the facility. The implementation in SPIS of ion energy distribution analysis would allow to move a step forward in plume model validation. Besides, the inclusion of ion-neutral elastic collisions would probably produce more realistic plume profiles and energy distributions.

Acknowledgments

This work is being carried out under the ESA contract N. 22730/09/NL/SFe. We would like to thank the SPIS core team from ONERA and Artenum for their precious support concerning the SPIS software. We also wish to thank all the people involved in the AISEPS project for very interesting and fruitful discussions. M. Wartelski thanks Nuno Loureiro for his precious contribution at the beginning of the project.

References

[1] Bulit, A., Perez Luna, J., Gonzalez del Amo, J., Lotz, B., Feili, D., and Leiter, H.,"Experimental Investigations on the Influence of the Facility Background Pressure on the Plume of the RIT-4 Ion Engine,"*IEPC 2011*, Paper IEPC-2011-014 (submitted for publication).

[2] SPIS's Home Page, www.dev.spis.org/project/spine/home

[3] Roussel, J.-F, et al.,"Spacecraft Plasma Interaction Software (SPIS): Numerical Solvers - Methods and Architecture,"*Proceedings of 9th Spacecraft Charging Technology Conference*, Tsukuba, Japan, JAXA-SP-05-001E, April 2005.

[4] Roussel, J.F.,"SPIS Open Source Code: methods, capabilities, achivements and prospects,"*IEEE Transactions on Plasma Science*, Vol. 36, No. 5, 2008, pp 2360-2368.

[5] Birdsall, C.K.,"Particle-in-Cell Charged-Particle Simulations, Plus Monte Carlo Collision With Neutral Atoms, PIC-MCC,"*IEEE Transactions on Plasma Science*, Vol. 19, No. 2, April 1991.

[6] Tajmar, M., Sedmik, R., Scharlemann, C.,"Numerical Simulation of SMART-1 Hall Thruster Plasma Interactions," *Journal of Propulsion and Power*, Vol. 25, No. 6, November-December, 2009.

[7] Bigioni, L., and Passaro, A.,"Plasma Thruster Plume Simulation: Effect of the Plasma Quasi Neutrality Hypothesis",34^{th} *AIAA Plasmadynamics and Lasers Conference*, 23-26 June 2003, Orlando, Florida, AIAA-2003-4173.

[8] Tajmar, M, et al., "Charge-Exchange Plasma Contamination on SMART-1: First Measurements and

Model Verification,"40th *Joint Propulsion Conference*, Ft. Lauderdale, FL, July 2004, AIAA-2005-3437, 2004.

[9] Bondar, E.A, Schweigert, V.A., Markelov, G.N., and Ivanov, M.S.,"Assessment of CEX Ion Backflow of SPT-100 Thruster,"*Proceedings of International Symposium on Rarefied Gas Dynamics*, Vol. 58, pp. 278-285, NY, 2001.

[10] Miller, J.S., et al.,"Xenon charge exchange cross sections for electrostatic thruster models,"*Journal of Applied Physics*, No. 91, p.984-991, 2002.

[11] Snyder, J.S. et al,"Performance Evaluation of the T6 Ion Engine,"46th *AIAA, ASME, SAE and ASEE Joint Propulsion Conference and Exhibit*, 2010.

[12] Tajmar, M., Mitterauer, J., and Wang, J.,"Field-Emission-Electric-Propulsion (FEEP) Plasma Modeling: 3D Full Particle Simulations,"35th *AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, Paper AIAA-1999-31133, Los Angeles, California, June 1999.

[13] Goebel, D., et al, "Fundamentals of Electric Propulsion: Ion and Hall Thrusters,"*JPL Space Science and Technology Series.*

[14] King, L. B.,"Transport-Property and Mass Spectral Measurements in the Plasma Exhaust Plume of a Hall-Effect Space Propulsion System," Ph.D. Dissertation, Dept. of Aerospace Engineering, University of Michigan, Ann Arbor, MI, May 1998.

[15] Oh, D.Y., Hastings, D.E., Marrese, C.M., Haas, J.M., and Gallimore, A.D.,"Modeling of Stationary Plasma Thruster-100 Thruster Plumes and Implications for Satellite Design,"*Journal of Propulsion and Power*, Vol. 15, No. 2, March-April 1999.

[16] Boyd, I.D., Garriges, L., Koo, J., and Keidar, M.,"Progress in Development of a Combined Device/Plume Model for Hall Thrusters,"*36th Joint Propulsion Conference*, Paper AIAA-2000-3520, Huntsville, Alabama, July 2000.

[17] Theroude, C., Provost, S., and Chéoux-Damas, P.,"Overview of Astrium Modeling Tool for Plasmic Thruster Flow Field Simulation,"28th *International Electric Propulsion Conference*, Paper IEPC-2003-267, Toulouse, France, March 2003.

[18] Manzella, D. H., and Sankovic, J. M., "Hall Thruster Ion Beam Characterization,," AIAA paper 95-2927, July 1995.

[19] Passaro, A., Vicini, A. and Biagioni, L.,"Plasma Thruster Plume Simulation: Effect of Vacuum Chamber Environment," AIAA Paper 2004-2357, June-July 2004.

[20] Matéo-Vélez, J.C., Roussel, J.F., Sarrail, D., Boulay, F., Inguimbert, V., and Payan, D.,"Ground Plasma Tank Modeling and Comparison to Measurements,"*Transactions on Plasma Science*, TPS2470, 2008.

[21] Tajmar, M., Marhold, K., and Kropatschek, S.,"Three-Dimensional In-FEEP Plasmadiagnostics,"28th *International Electric Propulsion Conference*, Paper IEPC-2003-0163, March 2003.

[22] Bonelli, E., et al.,"A 3.000 Hours Endurance Testing of RIT-22 Thruster in the New Aerospazio Test Facility,"29th *International Electric Propulsion Conference*, Paper IEPC-2005-212, Princeton University, November 2005.

[23] Prioul, M., et al.,"PPS1350 Qualification Status and Performances,"4th *International Spacecraft Propulsion Conference*, Paper ESA SP-555, Cagliari, Italy, October 2004.

[24] Ceccanti, F., et al.,"3200 hours Endurance Testing of the Lisa Pathfinder FT-150 Thruster,"31st *International Electric Propulsion Conference*, Paper IEPC-2009-170, Ann Arbor, Michigan, USA, September 2009.

[25] Tajmar, M., González del Amo, J., Estublier, D., and Saccoccia, G.,"Modelling and Experimental Verification of Hall and Ion Thrusters at ESTEC,"3rd *Spacecraft Propulsion Conference*, Paper ESASP-465, Cannes, France, 2000.

[26] Manzella, D., et al.,"Hall Thruster Plume Measurements On-Board the Russian Express Satellites,"27th International Electric Propulsion Conference, Paper 2001-211217, Passadena, California, 0ctober, 2001.