Electric Propulsion Plume Modelling: OHB approach

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Abstract: **In order to correctly assess the interactions between the electric propulsion subsystem and the spacecraft, modelling tools are necessary to predict effects such as materials sputtering, disturbing forces and torques and contamination. The OHB approach is based on a compromise between using a simplified ray-tracing approach and a more complex hybrid Particle-In-Cell method. This paper details each of the methods and their physical assumptions. Controlling the numerical and physical convergence of the simulation in the case of a PIC method is explained whereas the limitation of the ray-tracing approach is described. The erosion modelling approach used in the industry is discussed in this paper as well as the plume modelling. The main outcome from our work is the confirmation that despite the advantages and shortcomings of the different tools, the quality of the results depends mostly on the choice of input data.**

Nomenclature

r = distance from the thruster exit plane to the far field
T_e, $T_{e,0}$ = Electron temperature, Electron reference temperature
n_e, n_0, n_{ij} = density of electrons, density reference of electrons, density of atomic species i
α = adiabatic exponent
q_e = charge on an electron
λ_D = Debye length
ϕ , ϕ_0 = Potential, Potential reference
C_d = Current density
dS = Surface crossed by ions
I, I_{rev} = Current, Integrated current
θ = Angle of rotation
φ = Angle around thruster axis
ϵ_0 = permittivity of free space
k_b = Boltzmann's constant
T_i = ion temperature
χ = ratio of the potential change over electron temperature
ξ = ratio linking potential change to the Debye length
ζ = criteria linkingχ, ξ and mesh resolution
η_a = acceleration efficiency
Y = Erosion yield

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I. Introduction

OHB is a family-run company with the character of a medium-sized business funded during the 1980s by Professor Fuchs along with Christa Fuchs. From modest beginnings to an internationally recognized and consistent player, OHB developed several satellites based on different propulsion systems. First, OHB built satellites based on chemical propulsion systems such as SAR-LUPE (radar) and the European navigation system Galileo. Then, OHB developed the so-called "SmallGeo" telecommunication platform based on a hybrid propulsion solution: chemical and electrical systems. In this case, the station keeping is achieved thanks to the Hall Effect Thrusters (HET).

Current developments are focused on ELECTRA and Heinich Hertz (H2SAT) satellites. The Electra platform is a full electric propulsion satellite. In this case, large HET thruster are mounted on a flexible boom and are used for both the orbit raising and the station keeping. Based on the SmallGeo platform, H2SAT station keeping will be performed by the HEMPT (High Efficient Multistage Plasma Thruster) electric propulsion technology. As a system engineering company, OHB is in charge of each its spacecraft design and need to make sure that the mission is successful. In this aspect, interactions between the electric propulsion induced plume and the spacecraft need to be analyzed and carefully studied.

In fact, the plume analysis interacts with several other subsystems: the Attitude Orbit Control System (AOCS), the power subsystem, the thermal subsystem and the payloads. The plasma plume could lead to unwanted forces and torques that could disturb orbit raising or station keeping manoeuvers. Due to the charged ions high velocity, sputtering of the materials can occur which then leads to properties changes. The solar array could experience power loss when their cells or interconnectors are impacted. Mirrors can suffer from sputtered materials deposition and transmission loss at end of life can be experienced. Same effect is observed if thermal radiators are in the direct view of the plume or are contaminated due to secondary deposition. This underlines the importance of the plasma plume modelling. Being able to predict these effects is crucial for the mission success and for an optimized design.

II. Modelling techniques

Multiple ways to model the plasma plume are possible. A smart trade-off between simplification and physical correctness of the simulation is necessary to build a sustainable approach. If simplification and quick answers to the projects need to be provided, then, a ray-tracing method could be the answer. The ray-tracing techniques are sometimes not able to model some plasma dynamics such as the charge exchange collision (CEX). If the design is complex and a high level of confidence is required, then a Particle-In-Cell method is needed. However, it has to be noticed that a PIC solution also needs to be simplified at a certain level. In the case of a system integrator like OHB, the modelling of the thrusters "inside" is discarded. It is rather the conditions at the exit plane of the thruster that are of interest. In fact, these conditions, which are crucial for a plume analysis, are not independent from the inside of the thruster and connect this domain to the far field.

A. Ray-tracing

The ray-tracing technique is quite easy to implement and is based on a simplified concept. The thruster is modelled as a point source and the ion current, ion energy and multiple charged ions fraction, specified as inputs. The charged ions are then transported to the far-field where the average current decreases following the $1/_{r^2}$ rule (see Figure 1). In addition, the ions are accelerated to a velocity, according to the thruster potential. The quality of the ray-tracing tool depends on the plasma modelling precision in the near field. Different methods can be imagined by injecting ions into the domain from experimental data, from a Particle-In-Cell (PIC) simulation or a probability distribution.

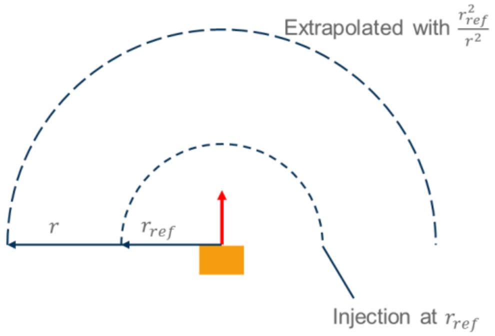


Figure 1. Ray-tracing method

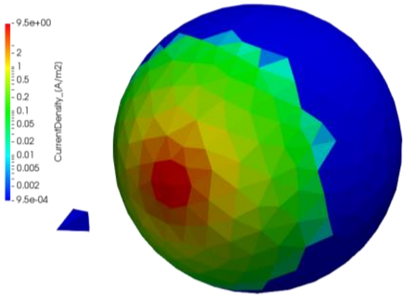


Figure 2. Simple case of shadowing calculation

The impact on a surface depends on the impinging angles, the ions average energy and its material. From these parameters, the erosion yield and applied forces and torques are deduced. Each surface of the spacecraft is modelled in 2D and the meshing is also used to detect any shadowing that could happen (see Figure 2). This method allows a quick way for modelling the spacecraft and does not require complicated meshing parameters. The meshing in this case is trivial, allows a flexible analysis and helps in achieving fast convergence. In fact, one has to check the gradient evolution on an impacted surface and be sure that the chosen mesh provides stable solution.

B. Particle-In-Cell

The PIC method used in OHB is a hybrid one: it combines PIC part and a DSMC one. Ions and neutrals are modelled via super particles. For each time step, the charge density and the electric potential are computed. The particles are then moved and generated. The electrons are modelled as fluid. The DSMC part is used to simulate the collision dynamic[1]. Two types of collisions occur: the elastic collisions and charge exchange collisions. Elastic collisions involve momentum exchange. The CEX exchanges happen when a fast ion collide with a slow ion and thus, describe the charge transfer between a fast ion and a slow neutral without any momentum exchange:

- Xe+(fast) + Xe (slow) → Xe+(slow) + Xe(fast)
- Xe++(fast) + Xe (slow) → Xe++(slow) + Xe(fast)

It has to be noticed that the ray-tracing tools cannot model the CEX effect. Modelling the CEX can be a great help for assessing the impact in the backflow of the Plume. As explained in a previous paper[2], the plasma potential is obtained by assuming quasi-neutrality. The electrons temperature is modeled in a polytropic relationship between electron temperature T_e and density n . ($T_{e,0}$ is a reference temperature, n_0 is a reference density)

$$T_e = T_{e,o}\left(\frac{n}{n_o}\right)^{\alpha-1} \quad (1)$$

The electric potential is then obtained in (3) by integrating the electron momentum balance (2).

$$nq\nabla\phi = \nabla(nkT_e) \quad (2)$$

$$\phi = \phi_o + \frac{kT_{e,o}}{q}\frac{\alpha}{\alpha-1}\left[\left(\frac{n}{n_o}\right)^{\alpha-1} - 1\right] \quad (3)$$

C. Convergence control

The extrapolation in the far field being rather simple in the ray-tracing case, the numerical and physical control of the simulation does not require sophisticated methods but modest rules. Each analysis needs to check that there are enough meshes on the studied surfaces, that the type of the structured mesh is the right one (rectangular of triangular cells), that the ions injection parameters are correct and that the shadowing calculations is accurate.

- **Current conservation**

In the case of the PIC calculation, OHB developed methods and tools that helps achieving convergence and gives confidence about the physical assumptions. The goal is to check the physical correctness of the simulation by linking the domain's meshing with different physical parameters. First step of a PIC simulation is to check if the simulation is conserving the physical quantities and is respecting the assumptions seen in last paragraph.

The current can be investigated and checked if it is conserved by integrating the current density over a surface which most of ion flux travels. By placing current rakes at different distances from the thruster, the quantity is integrated with regard to two angles defined in equations (4), (5) and Figure 3.

$$I = \iint_S cd \cdot dS \quad (4)$$

$$I_{rev} = \int_{\phi=0}^{\pi}\int_{\theta=-\frac{\pi}{2}}^{\frac{\pi}{2}} cd\, r^2 \sin\theta\, d\theta\, d\phi \quad (5)$$

A parametric analysis with different meshes have been carried out and it was found out that the coarser is the mesh, the more fluctuation in the current conservation is observed as seen in Figure 4.

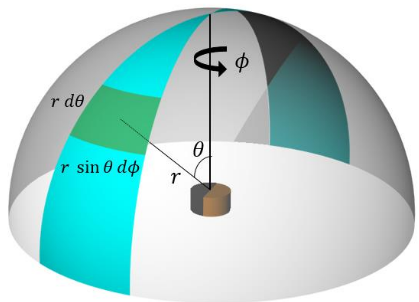


Figure 3. Current integration method

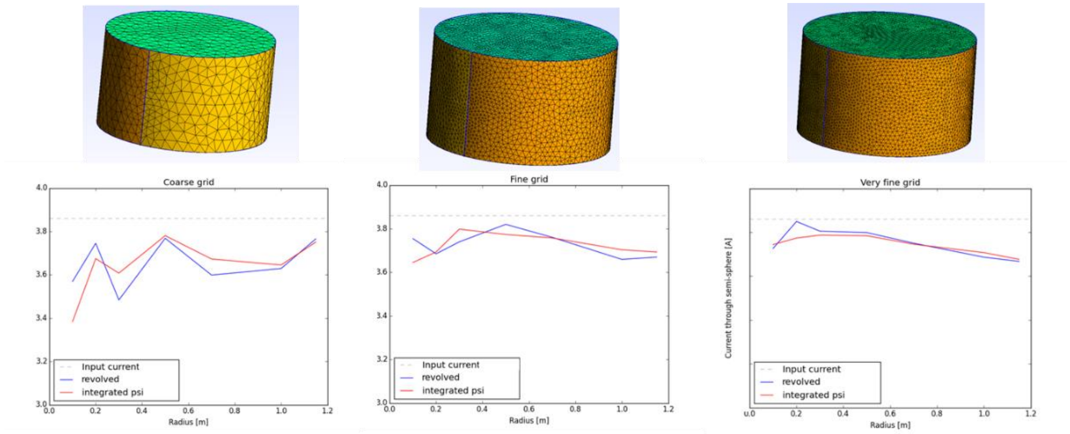


Figure 4. Mesh influence on the current conservation

- **Quasi-neutrality assumption**

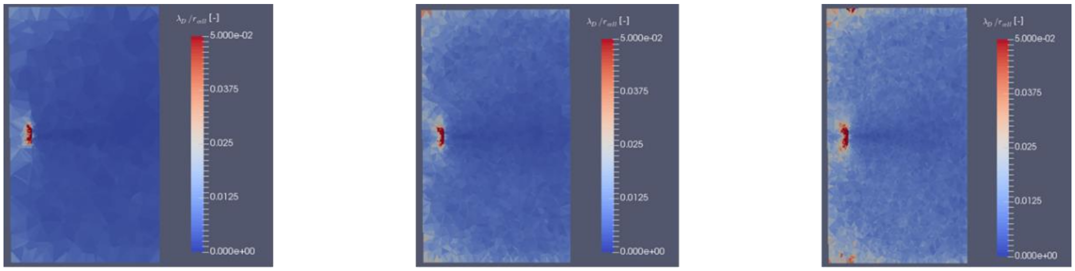
Second hypothesis to be checked is the quasi-neutrality assumption. Consider a plasma with quasi-neutral ion and electron densities, when placing a surface in a plasma, the surface gets charged negatively because the more mobile electrons hit the surface more often. The negatively charged surface will start repelling electrons. Around the surface, a layer with more ions than electrons is formed. This is called the Debye sheath[3].

According to the quasi-neutrality assumption that is used by the PIC tool, the number of electrons is equal to the number of ions in each cell volume. However, this assumption is violated within this Debye sheath.

The Debye sheath can be characterized by its Debye length λ_D and the potential ϕ vs. electron temperature T_e variation. Debye length λ_D is expressed as follow:

$$\lambda_D = \sqrt{\frac{\epsilon_0 k_b / q_e^2}{n_e/T_e + \sum_{ij} j^2 n_{ij}/T_i}} \quad (6)$$

In order for the simulation to remain valid by respecting the quasi-neutrality assumption, the grid near a surface must not be too fine. If the cell size is small compared to the Debye sheath thickness, the assumption does not hold anymore. As seen in Figure 5, some zones near walls, can be problematic if the meshing is too fine.



Coarse mesh **Fine mesh** **Very fine mesh**

Figure 5. Debye length and mesh variation

In addition, the thickness of the Debye sheath depends on the ratio χ which is the potential change Δϕ over electron temperature T_e and is related to the Debye length through the parameter $\boldsymbol{\xi}$. These ratios[3] χ and $\boldsymbol{\xi}$ are defined in (7) and (8), linked together in (9). To check if the assumption is respected, a convergence criteria ζ mixing all previous parameters is introduced in (10). Depending on the value of this parameter, the respect of the quasi-neutrality assumption is checked.

$$\chi = \frac{q_e \, \Delta\phi}{k_b \, T_e} \, (7)$$

$$\xi = \frac{d}{\boldsymbol{\lambda_D}} \, (8)$$

$$\xi = 1 + 0.35\,\chi \, (9)$$

$$\zeta = \mathrm{f}(\chi, \xi, mesh) \, (10)$$

III. Plume modelling

Plume models are usually compared to experiments characterizing the current density and the energy distributions with regard to the angle. The current density can be reasonably fit by injecting the correct physical parameters at the thruster exit plane (geometry, ionization efficiency, acceleration, electron temperature variation ...). These parameters are usually available for typical HET thrusters (such as SPT100) and therefore, the modelling can be backed by experimental characterization.

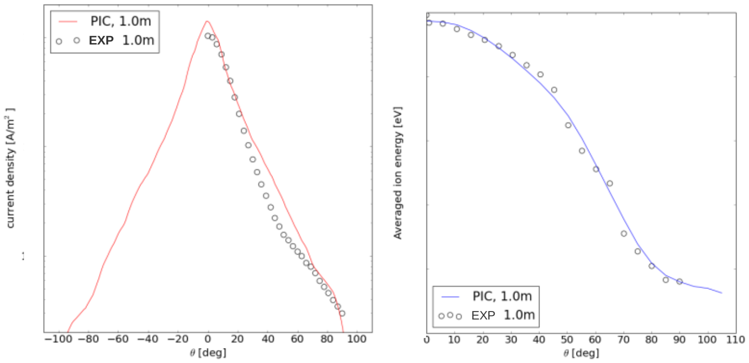


Figure 6. Current density and energy distribution

As an example, the electron temperature evolution from the near field to the far field influences the shape of the plume as seen in Figure 7. The electric field variation depends on the adiabatic exponent defined in equation (1) and the experiments^4 showed that this parameter varies for each thruster (PPS100 and PPS1350).

We can notice here that these phenomena are not sufficiently apprehended in the community. In fact, the adiabatic exponent varies from one thruster to another. An effort has to be made in order to better model the plume and to integrate electron temperature measurements in standard EP thrusters' characterization.

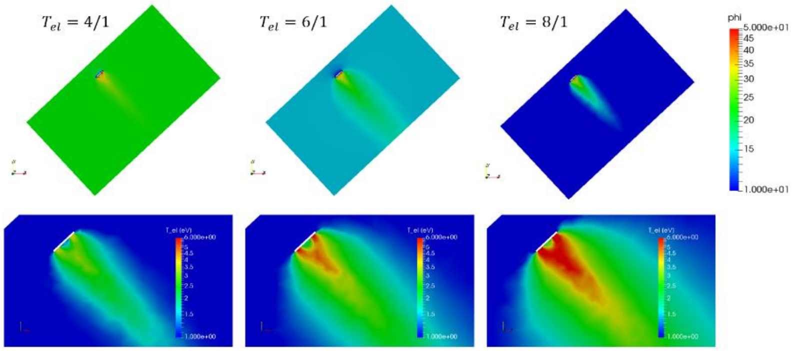


Figure 7. Electron temperature evolution from near field to far field and impact on the Plume

Finally, the ions energy distribution can be controlled through the thruster acceleration efficiency for larger angles. In this case, in order to meet the correct thrust value, the acceleration efficiency defined in equation (11), can be optimized to fit the energy distribution and thus, avoid overestimation at large angles.

$$\eta_a = \frac{\frac{1}{2}m\bar{v}^2}{e\Delta V} \quad (11)$$

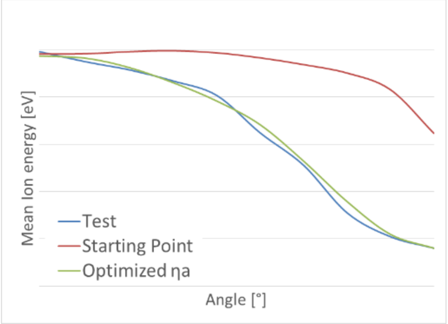


Figure 7. Optimized acceleration efficiency impact on energy distribution

IV. Erosion modelling

The erosion modelling depends on the energy of the impinging ions and their angles. The Erosion yield Y represents the ratio between the sputtered atoms and the incident ions. Generally, experiments are carried out to characterize monolayers materials for some energy and angles ranges.

Therefore, sputtering of materials have been characterized by choosing an empirical approach. In fact, in a spacecraft configuration, ions impinging on a surface occurs at much larger energies and angles scales than those available in one experiment. Consequently, a fitting function is needed and several models co-exist that link the erosion yield to the impinging ions energy and their angle.

Yield over energy	Yield over incidence angle
Yamamura-Tawara[5]	Yamamura[8]
Garcia-Rosales-Bohdansky[6]	Oechsner[9]
Rosenberg and Wehner[7]	

Table 1. Erosion models

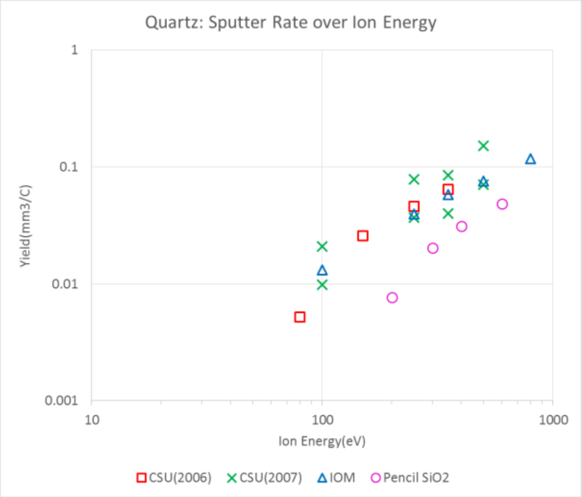


Figure 8. Yield evolution in function of the Energy

OHB gathered the existing experiments inside an internal database. Our database combines international data published by CSU in the USA, MAI in Russia and IOM in Germany, among others. By plotting the same material properties, the experimental data showed that these yields are in the same range (see Figure 8). As example, for the quartz, available data from IOM matches in some cases data from CSU (2006) and other CSU (2007).

However, these tests do not take into account essential parameters such as surface roughness, the yield evolution in time, multilayer material and surface binding energy. In an industrial context, modelling such a microscopic approach is a big challenge. Therefore, a method combining both approaches is currently under investigation in order to not neglect the aforementioned parameters.

Nonetheless, as specified in previous work[10], the PIC approach has been validated to be used in an industrial context by reproducing well known on-ground experiments. In the case of the erosion, the SPT100 experiment[11] has been modelled and a great discrepancy at larger angles was observed. By optimizing the plume modelling, the new results show better estimation at large angle. The two numerical tools (ray-tracing and PIC) are in the same range as the experiment.

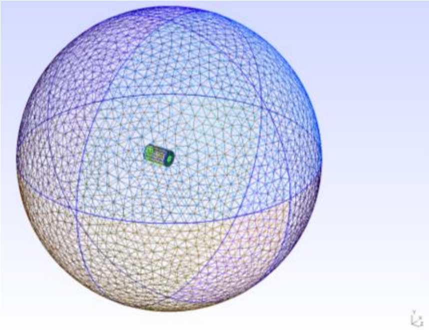


Figure 9. SPT100 numerical step up

Method	$\boldsymbol{\theta = 15°}$	$\boldsymbol{\theta = 30°}$	$\boldsymbol{\theta = 45°}$
Ray-tracing	28%	31%	186%
PIC Tool	29%	12%	196%

Table 2. SPT 100 experiment and modelling results

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V. Conclusion: modelling approaches complementarity

This strategy chosen by OHB offers complementarity and flexibility in the design phases especially for complex cases where orbit raising with a boom needs to be studied for example. The starting point is then to model as good as possible the current density, the energy distribution and fit them to a dedicated plume experiment. By connecting the PIC and the ray-tracing tools, the plume and its dependence on vacuum conditions can first be investigated by PIC modelling and then be injected into ray-tracing simulations for fast assessments. In a later project phase, a PIC solution can be more adequate for high precision predictions (impact on larger angles) while the ray-tracing approach is more suited for extensive parametric studies (optimize thruster location and rotation for a full Electric satellite).

In fact, even if the convergence control of a PIC simulation is harder to achieve compared to the ray-tracing technique, the PIC approach is however able to model situations where the ray-tracing is not adapted. As example, when an object, such as an antenna, is located at larger angles of the plume, the CEX is the prominent effect that leads to erosion.

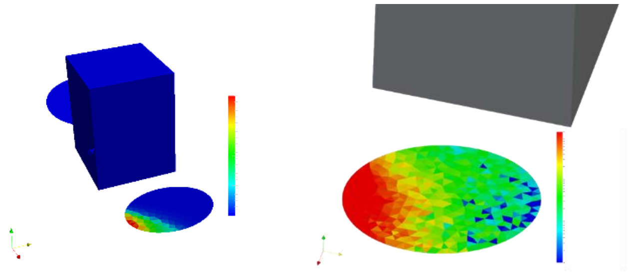

Figure 10. CEX effect, impact on larger angles modelled with ray-tracing (left) and PIC (right)

On the other hand, if a small object has to be modelled, like the silver interconnector, the PIC simulation will experience troubles that cannot be tackled due to the quasi-neutrality assumption violation and due to large mesh gradients in the simulations. For example, the silver interconnectors of a solar array are in order of some millimeters and are located between the solar cells. Modelling them is essential in deriving the correct spacecraft design.

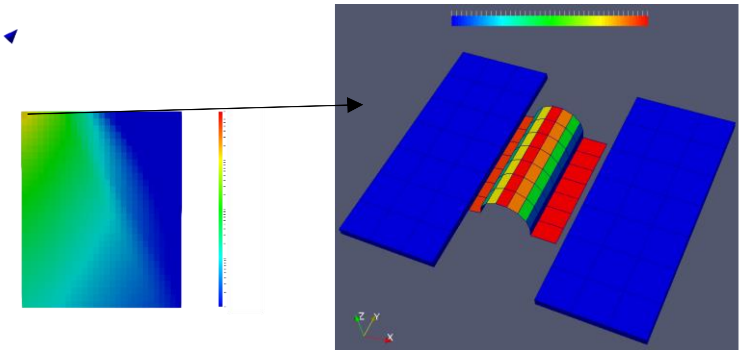

Figure 11. Silver Interconnector modelling

In conclusion, a lot of efforts have been made to achieve plume modelling that is balanced between answering OHB industrial needs and respecting physical correctness of the plasma dynamics. Nevertheless, better experimental characterization of the plume and the materials is essential in correctly predicting the impact on the spacecraft. In this sense, OHB would like to insist on bringing all the scientific community together to draw a roadmap that tackles all misunderstood or neglected topics.

Acknowledgments

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