Model and Experimental validation of spacecraft-thruster Interactions for electric propulsion thrusters plumes

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Lara Popelier[1], Christophe Théroude[2], Dimitry Loubère[3]
Airbus Defence and Space, 31 rue des Cosmonautes, 31400 Toulouse, France

Käthe Dannenmayer[4]
ESTEC, European Space Agency, Keplerlaan 1, PO Box 299, NL-2201 AZ Noordwijk, The Netherlands

Pierre Sarrailh[5], Sébastien Hess[6],
ONERA, Space Environment Department, Toulouse, France

Mario Merino[7], Pablo Fajardo[8], Eduardo Ahedo[9]
Aerospace Engineering Department, Universidad Carlos III de Madrid, Avda. de la Universidad 30, 28911 Leganés (Madrid), Spain

Stéphane Mazouffre[10]
ICARE, CNRS, 1C avenue de la Recherche Scientifique, CS 50060, 45071 Orléans cedex 2, France

Gabriel Giono[11]
Department of Space and Plasma Physics, School of Electrical Engineering, KTH–Royal Institute of Technology, SE-100 44, Stockholm, Sweden
Leibniz-Institute of Atmospheric Physics (IAP), Kühlungsborn, Germany

Jón Tómas Guðmundsson[12]
Department of Space and Plasma Physics, School of Electrical Engineering, KTH–Royal Institute of Technology, SE-100 44, Stockholm, Sweden and Science Institute, University of Iceland, Dunhaga 3, IS-107 Reykjavik, Iceland

Nickolay Ivchenko[13]
Department of Space and Plasma Physics, School of Electrical Engineering, KTH–Royal Institute of Technology, SE-100 44, Stockholm, Sweden

[1] Advanced Physics Modelling Engineer, Advanced Physics Group, lara.popelier@airbus.com
[2] Architect, Check-out Solutions, christophe.theroude@airbus.com
[3] Electric Propulsion Engineer, Electric Propulsion Group, dimitry.loubere@airbus.com
[4] Technical Officer, Electric Propulsion Laboratory, ESA, kathe.dannenmayer@esa.int
[5] Research scientist, ONERA, Pierre.Sarrailh@onera.fr
[6] Research scientist, ONERA, Sebastien.Hess@onera.fr
[7] Assistant Professor, Universidad Carlos 3 de Madrid, mario.merino@uc3m.es
[8] Assistant Professor, Universidad Carlos 3 de Madrid, pfajardo@ing.uc3m.es
[9] Professor, Universidad Carlos 3 de Madrid, eahedo@ing.uc3m.es
[10] Director of Research, CNRS ICARE, stephane.mazouffre@cnrs-orleans.fr
[11] Post-doctoral research fellow, KTH, ggiono@kth.se
[12] Guest professor, KTH, tumi@hi.is
[13] Associate professor, KTH, nickolay@kth.se

Abstract: it is desirable to develop and have access to plasma models usable in day-to-day industrial processes which are able to reproduce with sufficient accuracy the electric field build-up and potential decay downstream the thruster and around the satellite, to effectively predict the ions trajectory towards the surfaces. An experimental validation of those models is mandatory to gain confidence in their adequacy. In this context, the MODEX study, funded by the European Space Agency (ESA) and involving a consortium led by Airbus Defense and Space, aims at: i) identifying the key physical processes governing electron cooling and electric field build-up downstream the thruster in the far field, ii) proposing models of electron cooling that are physically representative and simple enough to be implemented in the SPIS software, iii) experimentally validating on-ground at ESTEC-EPL those models using a typical EP thruster used on telecom platforms, and tuning the model to the data, iv) performing system applications including erosion analyses, using both the data obtained and the models implemented, and compare the two approaches. The first 3 phases have been done so far and are described in this paper.

Nomenclature

ji	=	ion current density [$A.m^{-2}$]
ne	=	electron density [m^{-3}]
Te	=	electron temperature [K]
Vp	=	plasma potential in the plume [V]

I. Introduction and scope

Electric Propulsion (EP) is a key enabling technology, in particular for missions where mass saving constitutes a decisive advantage, like geostationary telecom missions, planetary exploration and low thrust missions. Thanks to ESA and European industry efforts, unique capabilities have been developed in Europe in this field. In particular, Airbus Defence and Space (Airbus DS) took advantages of these capabilities, and was the first European company to successfully develop commercial satellites using electrical propulsion, based on Hall Effect Thrusters (HET). Airbus Defence and Space has 15 years of Electric Propulsion flight experience and 20 years of experience in EP-SC interaction analyses with own-developed simulation tools. Indeed, mounting electrical propulsion on-board requires to master all the related system aspects, some of them being quite new with respect to those induced by classical propulsion systems. In particular, the interactions between the highly energetic and charged plume and the surrounding spacecraft raise several issues at system level that have to be predicted during the design phase: dynamic effects, erosion, contamination, interactions with RF beam, electromagnetic interferences and spacecraft charging. Moreover, for system primes, margins reduction and design optimization are constant objectives requiring accuracy and reliability improvements of these predictions. Space industry is currently observing an increasing interest for Electric Propulsion and its implementation on both scientific and telecommunications missions. This leads to increasing needs of EP-SC interactions analyses of new configurations to help architecture trade-off as well as detailed design.

One of the main constraints for accommodation of electric thrusters and therefore for architecture choice is the erosion induced by the plasma plumes on satellite surfaces, some of which are very sensitive like solar array interconnectors or antenna layers. Also, eroded parts contaminate other satellite surfaces and equipment. Some of the new architectures under study are exotic compared to the platforms already used and appear to be extremely challenging from the point of view of erosion. Erosion needs to be assessed as accurately as possible because it will have direct impact on the choice of future architectures and consequently on competitiveness of European satellites. Currently, plume induced erosion on satellites is estimated through simulations with plume models which are necessarily simplified due to industrial and computation constraints. For a given surface material and ion type, the level of erosion caused by one ion depends on the ion energy and incident angle. Those two, when reaching the surface, are heavily influenced by the electric field path the ion has followed from the thruster to the surface: simulations shall thus reproduce the electric field map as realistically as possible. Therefore a good description of the electron dynamics around the surfaces shall be provided to be able to properly model the movement of the ions towards them. Moreover, a crucial issue in the EP thruster performance is achieving better plume collimation. Decreasing the plume divergence should reduce the erosion of surfaces, particularly the solar panels, by impacting ions. Furthermore, a less divergent plume should result in a smaller interference with the radiofrequency transmission that is used for communication. One of the major sources for the plume divergence is the plasma pressure; and the extent of the divergence depends on the evolution of the electron temperature [RD07]. A previous ESA study, called AISEPS (Assessment of Interactions between Spacecraft and Electric Propulsion Systems) [RD01], has enabled to significantly improve the modeling capability of a plasma plume expansion around a spacecraft. Indeed, it offers the unique possibility with the open source software SPIS (Spacecraft Plasma Interaction Software [RD04]) to simulate in a consistent way the plasma expansion, the spacecraft charging and the current collection. Nevertheless, the computation of the electric field map of a near-collisionless plasma expanding from a point or a surface (e.g. a plasma thruster plume in this application) to infinity and surfaces (e.g. satellites) is not a trivial problem. Indeed, the codes most widely used in industry, because of their highly favourable trade-off between accuracy and computational requirements, are PIC-fluid codes where heavy species are modelled as superparticles and electrons as a fluid. In an unmagnetized medium and for usual spacecraft environment conditions, electrons from the emitted plume constitute a population confined by the electric field self-created by the plasma. Therefore, except from small drifts required for conservation of the electric current and the spacecraft charging state, the electron cloud is at quasi-static equilibrium, between the electric force and pressure. This has led too many codes to implement the classical Boltzmann relation (with constant temperature) as the equilibrium condition. Unfortunately, the tenuous plasma plume is weakly collisional, global thermodynamic equilibrium does not apply, and the cloud cannot be assured to be Maxwellian. In fact, the constant temperature model leads to the plasma electric potential dropping to minus infinity far downstream the plume and thus to an infinite supply of energy, which are clearly non-physical. There is limited experimental evidence of electron cooling in the far plume, but the physical mechanism behind that 'collisionless cooling' and proper scaling laws for it are unavailable, in spite of a long-time research effort by different plasma physics communities. In some codes, like SPIS, electron cooling has been provisionally tackled by using a polytropic equation of state with the polytropic coefficient being adjusted phenomenologically. This patch works fine since it leads to finite and adjustable potential falls between the thruster exit and the undisturbed environment. However, this is just a phenomenological fitting that teaches nothing about the cooling mechanism and the parameters and conditions that control it and lacks any predictability. Therefore, it is desirable to develop and have access to plasma models usable in day-to-day industrial processes which are able to reproduce with sufficient accuracy the electric field build-up and potential decay downstream the thruster and around the satellite, to effectively predict the ions trajectory towards the surfaces. An experimental validation of those models is mandatory to gain confidence in their adequacy.

In this context, the MODEX study, funded by the European Space Agency (ESA), thus aims at:

- identifying the key physical processes governing electron cooling and electric field build-up downstream the thruster in the far field and around the satellite surfaces with their own potentials,
- proposing models of electron cooling that, on the one hand, are physically representative and, on the other hand, are simple enough to be implemented in SPIS without incrementing much the computational requirements,
- implementing electron models in SPIS in order to model self-consistently plume forming,
- experimentally validating on-ground at ESTEC-EPL those models using a typical EP thruster used on telecom platform, and tuning the model to the data,
- performing system applications including erosion analyses, using both the data obtained and the models implemented, and compare the two approaches.

The consortium led by Airbus DS to answer the ESA study involved the following key participants with respective tasks: Airbus DS and Universidad Carlos 3 de Madrid (UC3M) firstly gathered the state-of-the-art on plume, erosion and electron cooling data. Then UC3M proposed and improvement of the electron cooling modelling of an EP thruster and ONERA implemented it in the SPIS software. In parallel, a test campaign on a SPT100 fired by Airbus DS was performed at ESTEC-EPL with electrical diagnostics from a team consisting in researchers from CNRS ICARE and the Royal Institute of Technology in Stockholm (KTH). Finally, validation of models implemented in SPIS, erosion analysis and comparison with simulation approaches are performed by ONERA and Airbus DS. The present work presents the three first tasks of the study.

II. Modelling and implementing the electron cooling behavior

A. State-of-the-art of existing experimental results and models of plasma plume

The study began with a review of existing experimental results (both in laboratory and in-flight) and models of plasma plumes, identifying the main aspects of the plasma response, and in particular, the electron temperature, electron cooling, and electric potential which constitute the objects of study of the present project. EP configurations in telecommunications satellites and erosion data have been also briefly reviewed.

As evidenced by the experiments, plasma plumes are subdivided into a near region, where collisions, residual electric and magnetic fields from the thruster, and 3D cathode effects dominate, and a far region, where the plasma density profile is smooth and single-peaked, and the evolution of the plasma is nearly collisionless, subject to the equilibrium between internal electron pressure, electrostatic forces, and the inertia of hypersonic ions. The transition between the two regions occurs a few thruster radii downstream from the thruster exit plane.

Laboratory tests, while useful to determine the primary ion properties, introduce a large uncertainty on the global, collisionless electron response in the far plume. This is due to the presence of the (conductive) chamber walls, the higher background pressure, and sometimes the artificial grounding of some elements in the thruster. In-space measurements are limited in number and in detail, but provide important information that allows identifying the key differences between laboratory and space conditions.

Measurements of electron temperature in the plasma plume of different thrusters reveal a smooth decrease in the axial direction (and also radially). Electron temperatures in the range of 0.5-10 eV are commonly reported. The decrease of electron temperature along the plume is usually slow, indicating a near-isothermal behavior in some cases. Temperature usually drops faster in the near region, especially in the case of Hall-Effect Thrusters (HET) where the residual magnetic field there is large. A single value of a cooling polytropic exponent γ does not seem to reproduce successfully the whole plume, and is thruster-, operating point-, and experiment-dependent.

Existing plume models vary in complexity and physical detail. On the lower end of the scale, fully-fluid models (like self-similar models) are adequate to obtain a first approximation of the plasma profiles. Hybrid PIC-fluid codes for the heavy species (ions, neutrals) are well suited to obtain the complex response involving the different populations of fast and slow particles. Electrons are routinely modelled as a fluid except in very heavy full-PIC simulations; the vast majority of the existing fluid electron models (including those implemented in SPIS) are simplified isothermal or polytropic electron models, which are not physically justified and need to be supported by experimental data to adjust all their parameters.

Kinetic modelling of the electron expansion is the recommended approach to recover the complex physics of the global electron response, including the collisionless cooling behaviour. Previous work at EP2-UC3M has successfully modelled the expansion of electrons in the fully-magnetized plasma plume of a magnetic nozzle, based on the conservation of the adiabatic invariant magnetic moment of each electron in a paraxial magnetic field. The kinetic evolution of the distribution functions of electrons and ions can be readily recovered then for a known electric field, given the distribution function at the initial condition. Iterating in this method, it is then possible to find the self-consistent electric field and the ion and electron response. Doubly-trapped electrons are found in this case. Electron collisionless cooling is observed in this case which can be fitted to piece-wise polytropic laws in different regions.

A similar approach has been proposed to model the expansion in an unmagnetized plasma plume. The 2D geometry and the increase of parametric space to one additional degree of freedom make this problem far more complex than the magnetized plume. However, the existence of a similar adiabatic invariant, based on the action integral in the radial motion of trapped electrons, is expected to allow a similar solution method. The obtained results shall be simplified enough to be implemented in SPIS as simple (but physically sound) electron cooling laws.

B. Electron cooling and electric field build-up processes and models

The detailed study of electron cooling mechanisms by UC3M is presented in another paper by Merino *et al* [3]. The implementation of the models in SPIS by ONERA is discussed in another paper by Sarrailh *et al* [4]. A summary is given in the present paper.

In their paper, UC3M describes the kinetic plasma plume model they have developed. Ions and electrons are modelled separately and self-consistency obtained by using them iteratively to find the stationary plasma and electric potential response in the plasma plume.

The fundamental assumptions of the model are that the plasma expansion is axisymmetric, paraxial (i.e. the plasma plume diverges slowly), collisionless, quasineutral, and that it has reached its steady state.

The electron model, which is the central piece of the plume model, solves Vlasov's equation for collisionless electrons semi-analytically, by exploiting the conservation of three adiabatic invariants in the electron motion. The ion model is simplified into their cold limit, paraxial fluid equations, and serves to close the problem.

The iterative procedure for the solution is as follows. An electric potential map is assumed as an initial guess. The electron and ion responses are computed for this electric potential. Then, evaluating the ion and electron density difference, and the deviation from a current-free plasma jet, a new electric potential guess is produced. The procedure is repeated until convergence and therefore a self-consistent plasma and electric potential response at the plume axis are achieved.

This plume model was then used to perform a parametric study for several values of the Mach number and the ion/electron mass ratio. It revealed a wide variety of electron distribution function behaviours in the plume.

As the simplified model to be implemented in SPIS should not be too computation-intensive, these parametric study results were used to define a single polytropic cooling expression:

$$\frac{T_e}{T_e(0)} \approx \left(\frac{n_e}{n_e(0)}\right)^{\gamma_{global}-1}$$

Different unique γ_{global} values were computed for a given set of Mach number and ion/electron mass ratio. The gamma value is then automatically computed by SPIS for each thruster as a function of the Mach number of the ions coming from the thruster and the ion mass emitted by each thruster..

A generalization of the previous approach has also been implemented in SPIS: it consists in a step wise definition of gamma as a function of plasma density.

III. Experimental set-up and results

The experimental set-up and results of the test campaign which occurred at ESTEC-EPL in the Corona vacuum facility are detailed in another paper written by Giono *et al* [5]. However a summary is given here.

An overview of the thruster and measurement set-up is shown in Figure 1. Airbus DS provided a 1.5 kW class SPT100 thruster while KTH and CNRS ICARE provided plasma diagnostics to monitor the plasma parameters and the ion current density respectively in the plume. Only KTH on-axis results are presented in this paper.

The SPT100 was installed in the ESTEC-EPL Corona vacuum facility, a large vacuum chamber (2 m in diameter and 4 m in length) and operated at six different operating points given in Table 1, where the discharge voltage and the mass flow rate of Xenon were varied. Background pressure was maintained at its lowest possible value for each operating point: 3.9e-5 mbar for a 2 mg/s mass flow rate and 7.7e-5mbar for a 4 mg/s mass flow rate.

Figure 1 shows two identical cylindrical Langmuir Probes (CLP) from KTH, with tip oriented parallel to ion stream lines that were used to investigate the plume. The probe tip was 0.2 mm in diameter, 5 mm in length and made of Tungsten, with an alumina body shielding the rest of the probe. One probe was installed on a translation stage mounted on a rotating arm, providing in particular on-axis measurements from 550 to 750 mm to the thruster exit (0 mm referring to the exit of the thruster). The second probe was mounted on a larger translation stage, providing measurements along the plume axis from 850 to 1550 mm. Measurements were thus obtained from 550 to 1550 mm along the plume axis. All measurements were performed in the horizontal plane located at the height of the thruster axis and recorded using a Keithley 2440 sourcemeter sweeping the probe voltage from -15 V to +35 V.

Figure 2 shows the electron density, electron temperature and plasma potential resulting from the CLP current-voltage characteristics for the six operating points given in Table 1. As expected, these three plasma parameters decrease in with the axial distance from the thruster exit plane center. More detailed analysis is given in another paper by Giono *et al* [5].

Discharge voltage	Anode mass flow rate	Discharge Current	Background pressure
[V]	[mg/s]	[A]	[mbar-N_2]
300	2.0	1.75	3.9e-5
300	4.0	3.83	7.7e-5
150	2.0	1.70	4.0e-5
150	4.0	4.17	3.9e-5
225	2.0	1.72	3.9e-5
400	2.0	1.78	3.9e-5

Table 1: Thruster operating points and resulting background pressures.

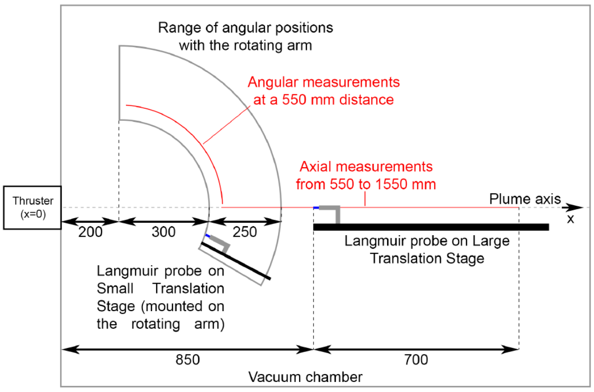

Figure 1: Positions of measurements of the KTH cylindrical Langmuir probes (CLP) inside the CORONA chamber. Distances are expressed in mm.

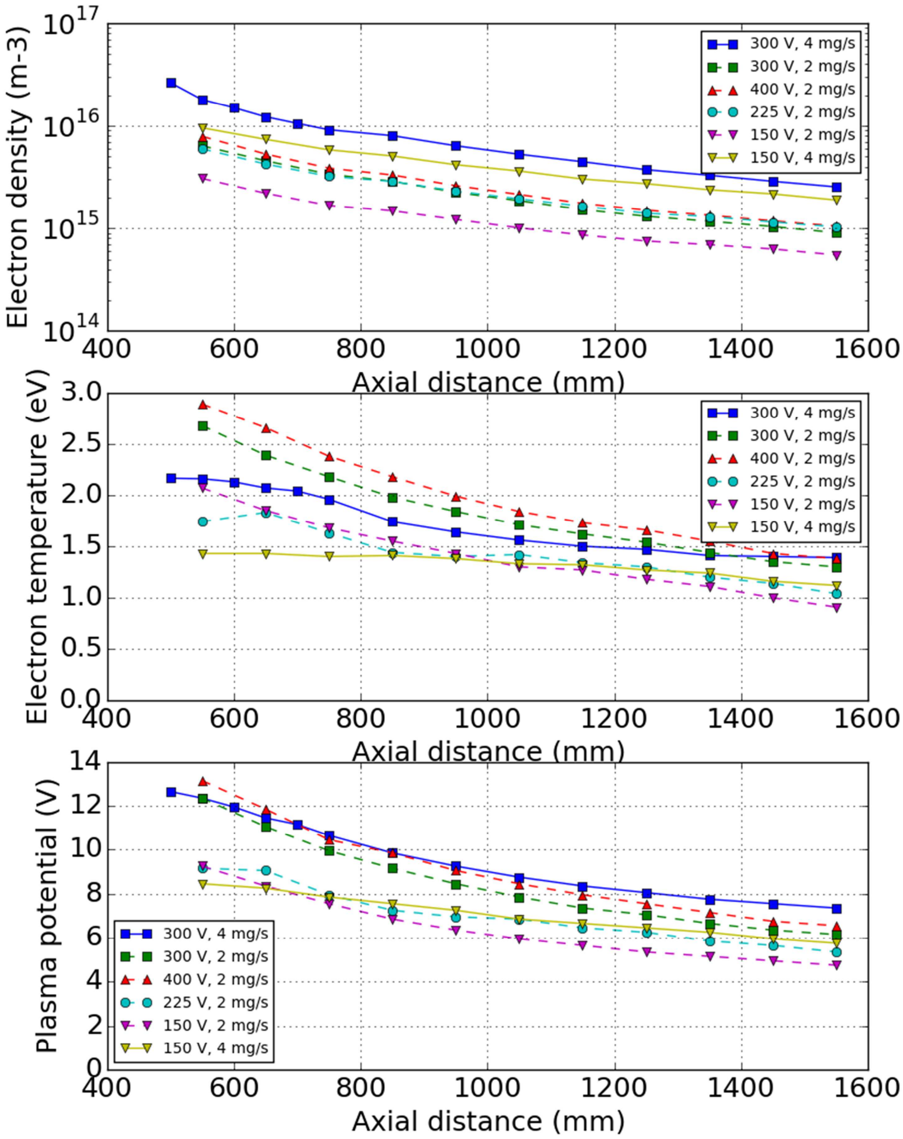

Figure 2: Electron density, electron temperature and plasma potential along the thruster axis resulting from current-voltage characteristics measured with CLP for the six operating points given in Table 1.

IV. Future work

Future work to be performed consists in validating the developed models by comparing them with on-ground and in-flight measurements. In addition to the physical validity of the implemented models, the relevance of SPIS to perform system analyses on a representative spacecraft will be assessed. The complexity to setup a simulation, the stability and the duration of the computation are indeed critical when using such a tool in an industrial environment, where numerous iterations are sometimes required during the early phases to refine the spacecraft design.

The first validation use case will be based on the results of the on-ground test campaign performed at ESA. ESA's vacuum chamber will be fully modelled in SPIS (see Figure 3), based on realistic dimensions of the chamber and taking into account the plasma source, the collection on the wall and the electric circuit coupling the plasma source and the plasma chamber. The background pressure of the vacuum chamber will also be modelled.

The results of the simulation will be compared with measurement. In particular the electron density, temperature and the plasma potential will be the most relevant values to validate the newly implemented temperature models.

The second test case consists in the realisation of the system simulation. The objective is to validate the relevance on the new model to perform simulation on a representative spacecraft model. As explained earlier, the current SPIS version does not allow an accurate simulation of the plasma potential evolution. Consequently, a particular attention will be paid on the following characteristics of the plume: plasma potential development particularly at large angles and in regions which are not directly exposed to the plume; energy of the charge exchange ions and induced erosion.

The third test case is the comparison of the SPIS software results with the SMART-1 satellite previously performed simulation. The SMART-1 configuration has been analysed in details by Airbus DS in the context of the AISEPS study. The main objective of this test case is the comparison of the different electrons models on a known configuration: indeed, it is proposed to compare simulation results for the following cases for electrons modelling: classical Boltzmann equation, Boltzmann equation with polytropic coefficient, new models for electrons. An example of SPIS simulation is given on Figure 4.

The last subtask aims at performing the analysis of the results obtained during the course of the project in order to propose the way forward for this activity. This task will be done in collaboration between the contributors of the project (i.e. in the experiments and in the numerical simulations). The results of the comparison between simulation and measurements as well as the comparisons between the different approaches on SMART-1 will allow assessing the validity and applicability to an industrial context of the new model. Evolution of the model or of its parametrization could be done further to this task to improve the modelling.

Finally, supported by the results of the tests and by the activity, we will summarize the results to clearly establish the limit and validity domains of the developed simplified models. This analysis will also support the establishment of a preliminary roadmap of recommended activities to overcome the identified limitations: models improvement, new tests, etc.

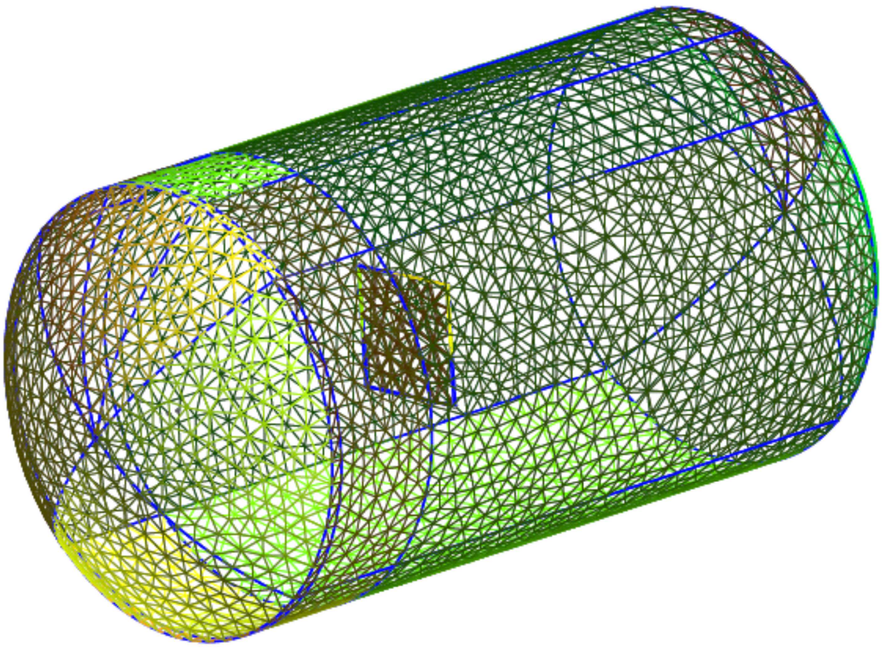

Figure 3: Simulation geometry and mesh: Jonas tank with plasma source, pumping system and collection plate

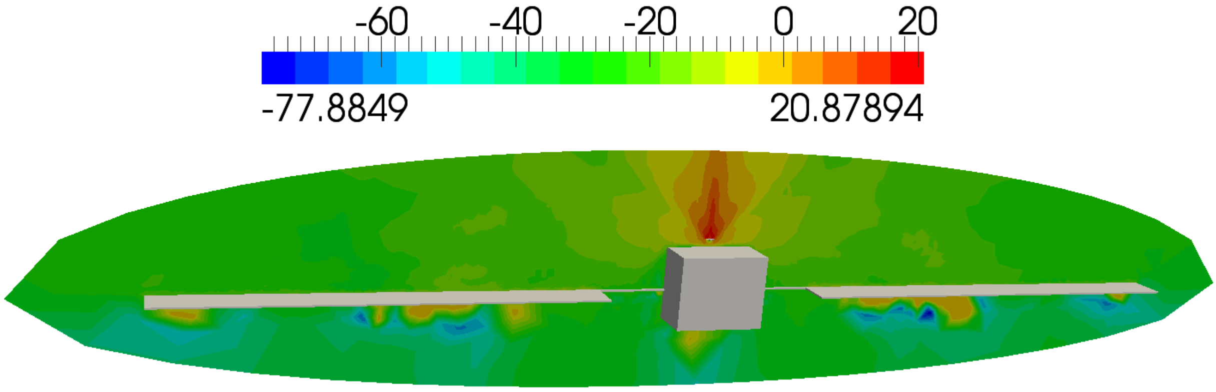

Figure 4: Example of SMART-1 simulation: plasma potential assuming a constant electron temperature.

V. Conclusion

The MODEX project goes on. After having thoroughly analyzed and simulated the behavior of the electrons in the plume, several models of electrons cooling have been selected and implemented in SPIS. A simplified approach is proposed as a baseline: it consists in a table enabling to compute the value of the polytropic coefficient for a wide range of conditions. The characterization of the plasma plume conducted in the ESA-EPL test facility has been completed. The next step will consist in the analysis of the measurement results. After this step, validation will be performed using SPIS to compare the simulation and the test measurements. Finally, system simulations will be performed in order to assess the utilization of SPIS to operationally support analysis at system level and identify the remaining gaps.

Acknowledgments

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